THE UNIVERSITY OF ALBERTA

ROOT DEVELOPMENT AND CROP GROWTH AS INFLUENCED BY SUBSOIL ACIDITY IN SOILS OF ALBERTA AND NORTHEASTERN BRITISH COLUMBIA

by

© RODNEY COLIN McKENZIE

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF DOCTOR OF PHILOSOPHY

in

Soil Plant Relationships

DEPARTMENT OF SOIL SCIENCE

EDMONTON, ALBERTA

FALL, 1973

ABSTRACT

Experiments were conducted in the field and greenhouse with acid soils of Alberta and northeastern British Columbia to determine the influence of subsoil acidity on acid-sensitive crops. The experiments involved treatments in which the soil acidity was neutralized by topsoil and subsoil liming and by topsoil liming alone to determine the separate effect of subsoil acidity on crop growth. Under field and greenhouse conditions subsoil acidity reduced the yields of top growth and subsoil root yields and penetration for both barley and alfalfa. The yield reductions were very closely correlated with the amount of Al (soluble in 0.02M $CaCl_2$) in the unlimed soils. Comparison of soil moisture levels and root yields on a limed and unlimed subsoil indicated that this was an effective means of showing how much the roots had penetrated the unlimed acid subsoil.

The damage to crops caused by subsoil acidity was eliminated by deep liming or by very large applications of P to the subsoil. Neither of these methods is economically feasible. An experiment with levels of subsoils acidity and subsoil temperatures indicated, in contrast to reports in the literature, no significant relationship between damage to roots by acid subsoils and temperatures of the subsoil.

A nutrient culture method was used to screen barley varieties for tolerance to Al toxicity. The Canadian varieties tested showed significant differences in tolerance to aluminum. The differences were not as large as those reported in the literature. This suggests a need for plant breeding to incorporate genes for Al tolerance.

A reconnaissance type survey was conducted to gain some idea of the extent of the agricultural areas where subsoil acidity is a problem. Maps were made to identify areas which contained soils with toxic levels of soluble Al.

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to Dr. M. P.K. Nyborg, Associate Professor of Soils, Department of Soil Science, under whose direction this study was undertaken. Thanks are extended to him for his assistance and encouragement with all phases of this study and for providing the photos of the field plots.

Thanks are also extended to the following:

Dr. F.D. Cook, Dr. J.A. Robertson, and Dr. G.R. Webster, all of the Soil Science Department, who served on the thesis committee and reviewed the manuscript;

Dr. J.M. Mayo, of the Botany Department, who served on the thesis committee, reviewed the manuscript, and provided assistance with constructing psychrometers;

Dr. K.G. Briggs, Department of Plant Science, who reviewed the manuscript;

Dr. C.D. Foy, U.S. Department of Agriculture, Beltsville, Maryland, who served as external examiner and reviewed the manuscript;

Dr. J.A. Toogood, Head of the Soil Science Department, for providing the facilities for this study;

Mr. W. Oborn, Department of Soil Science, for his assistance in analytical, statistical, and field plot work;

Mr. L. Hodgins, Provincial Soil and Feed Test Laboratories, for his assistance with analytical work;

Mr. D. Penney, Alberta Department of Agriculture, for allowing use of chemical data from some of his samples from his M.Sc. thesis;

Mr. T.A. Lord, of the Canada Department of Agriculture in Vancouver,

for providing samples from typical soil profiles for northeastern British Columbia;

Mr. V. Peck, Canada Department of Agriculture in Beaverlodge, for assistance with field plots in the Peace River area;

Messrs. M. Stachniak, T. Stachniak, G. Hawes, W. McKeen, E. Stolarchuk, B. Jackson, D. Fraser, D. Willmer, Ms. J. McCoy, and L. Gervais who assisted in constructing field plots and in laboratory work; and

The Canada Department of Agriculture, for providing financial assistance for this project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

INTRODUCTION

Extensive areas of soil in central and northern Alberta and northeastern British Columbia are formed on acid tills or contain horizons which are acid. These acid soils of Alberta and northeastern British Columbia often have an Ah, Ae, Bt, BC, Cca sequence of horizons. The most acid layer is usually the Ae or Bt horizon which may be sufficiently acid to prevent plant roots from reaching the C horizon below. Usually acid soils develop in regions of fairly high rainfall. Alberta's acid soils have developed in regions of limited rainfall with short summer seasons and low soil temperatures at depth and therefore present a somewhat unique condition. The effect of soil acidity on plant growth in cool, dry climates may be different from that in moist, temperate climates.

Until 1965 soil acidity was not considered an important agronomic problem in Alberta. It was assumed that because Alberta soils were of high base saturation, which Pierre (1931) stated was the most important factor in determining the fertility of acid soils, their acidity did not influence growth of crops. This assumption was based on a failure to realize that at a given degree of base saturation the highly weathered soils (with which Pierre worked) have a higher pH than montmorillonitic and illitic clays which are found in Alberta soils. Soil acidity was viewed mainly as a calcium deficiency problem and it was believed all of Alberta's acid soils have a lime horizon at depth and this lime horizon would supply sufficient calcium for plants.

Subsoil acidity is a problem which has received little direct attention by research workers in other parts of the world and no attention in Alberta. It is doubtful that surface applications of lime will

do much to overcome subsoil acidity problems because the low soil temperatures and limited rainfall on Alberta's acid soils combine to provide an environment where downward movement of lime would be very slow. If surface liming does not overcome subsoil acidity problems, then it is necessary to use species or varieties of crops which are tolerant to soil acidity.

The objectives of this project were to determine:

(1) the extent to which subsoil acidity restricts root penetration;

(2) the effect of subsoil acidity on crop yields;

(3) the agricultural areas in Alberta and northeastern British Columbia where subsoil acidity is a problem;

(4) the measurable chemical factors in the soil which restrict root penetration into acid soils;

(5) whether temperature is a factor which controls root penetration in acid soils and which will require different interpretations of soil test data of acid soils for Alberta as compared to other parts of the world;

(6) whether surface liming is sufficient to overcome subsoil acidity problems in an area of limited rainfall; and

(7) whether there are crop varieties available which are adapted to Alberta conditions and grow well on soils which have acid subsurface horizons.

LITERATURE REVIEW

Soil acidity was recognized by the Romans and liming the soil was described by Cato and Varro in the second century B.C. The east coast of Scotland has many acid soils. McFarlane (1683) described the liming of these soils in the 15th century. The prevalence of acid soils in Scotland explains the reliance on a crop tolerant to soil acidity, such as oats, and the Scots' use of oatmeal as a national food. The above two methods of farming acid soils --- growth of crops tolerant to acidity and liming to remove the soil acidity --- have not changed to the present.

Acid soils which limit plant growth are those having pH values appreciably below 7. Acidity is measured by determining hydrogen ion concentration (pH) in solution; however pH does not measure total or titratable acidity. Liming an acid soil results in an upward shift in pH, altered solubilities of minerals, altered ionic activities, altered microflora, and usually increased crop growth. Since liming simultaneously changes many of the soil properties which influence plant growth, it is difficult to identify the particular soil properties responsible for poor crop growth on acid soils.

Early research work attributed the damage to plant growth which occurred on acid soils to a shortage of calcium and to hydrogen ion toxicity. Bradfield (1923) at Missouri showed by means of titration curves that clays were weak acids and the idea came into prominence that acid clays were hydrogen saturated. In the USA the view that acid clays were hydrogen saturated was widely favored until the early 1950s. It was suggested that extractable aluminum was an artifact of chloride extraction

salts forming HCl, which dissolved precipitated aluminum hydroxides. Coleman and Harward (1953) heated clays which had been artificially saturated with hydrogen. The unheated clay produced a strong acid titration curve; the heated clay produced a weak acid titration curve. The unheated product showed little exchangeable aluminum; the heated clay showed considerable exchangeable aluminum. It was suggested that a hydrogen saturated clay soon becomes an aluminum saturated clay. Lin and Coleman (1960) showed aluminum saturated clays yielded about the same amount of aluminum with various normal unbuffered salt solutions. The quantity of aluminum released was similar to the quantity of calcium retained as an exchangeable cation. Lin and Coleman's work led to acceptance of the view that acid clays were saturated with aluminum. Current work in plant nutrition has shown that a number of factors are involved in soil acidity damage to plants.

Causes of Soil Acidity Damage to Plants

Hydrogen

The ease of determination of hydrogen and the titration data of Bradfield (1923) led to the view that clays were hydrogen saturated and hydrogen ions were the principal cause of soil acidity damage to crops. Arnon and Johnson (1942) varied hydrogen ion levels in culture solutions. They avoided pH shift by using large volumes of solution and mixing the solution. They found damage to plants occurred within one hour at pH 3, but most plants grew well above pH 4 to 5. They noted increases of calcium supply reduced the effect of hydrogen ion damage. Sutton and Hallsworth (1958) found that the calcium level was directly related to hydrogen

ion damage and also found hydrogen ion damage was most severe where the nitrogen level was low. They also reported that additions of calcium were ineffective in moderating damage of hydrogen ions when the solution was changed very frequently. Thus they assumed roots are capable of increasing the pH in their immediate environment by selective uptake of anions and release of bicarbonate ions. It appears that in most acid soils hydrogen ion activities are not sufficient to cause a major impairment to plant growth.

Calcium

Calcium has traditionally been added to acid soils in the form of lime as $CaCO_3$ or as $Ca(OH)_2$. Liming has the effect of reducing the activities of hydrogen and aluminum ions and increasing the calcium and magnesium supply. Cormack (1962) studied the role of calcium in formation of root hairs and calcium pectates in plant cell walls. He stressed the failure of plants to develop root hairs in acid soils and solutions. Lance and Pearson (1969) found short exposures to low concentrations of aluminum reduced the uptake by plant roots of water, calcium, magnesium, potassium, phosphorus, and nitrate. They found the reduction of calcium uptake occurred sooner than the reduction of uptake of the other constituents. The uptake by plant roots of calcium was inhibited from solutions which contained less than 200 ppm calcium. With a large excess of calcium (600 ppm), aluminum did not inhibit the uptake of calcium. They concluded aluminum replaced calcium in the plasmalemma, making it less permeable to water and ions. Not many soils show plant growth responses due to calcium applications when the soil pH is maintained constant, such as occurs when a neutral calcium salt like $CaCl_2$ is added to the soil. When cal-

cium deficiency is present either due to restrictions of calcium uptake by hydrogen or aluminum ions or to low levels of calcium in the growth medium, its effect on plant growth is pronounced. Jackson (1967) discusses a number of these effects. Growth of leaf margins and new leaves are restricted. Chromosome development and cell division are abnormal at low levels of calcium. Calcium deficiency causes many other imbalances in plant composition such as accumulation of carbohydrates in other parts of the plant. Low levels of calcium may result in failure of the plant to absorb sufficient nitrogen. Calcium may accelerate reactions involving amylases, phospholipases, and various kinases. Calcium also has the ability to regulate high energy phosphate supplied by activating ATP in root mitochondria and chloroplasts. Aluminum induced calcium deficiency is important in acid soils as shown by Long and Foy in 1970.

Aluminum

Aluminum ions become present in the soil solution below pH 5.5. The forms of soluble aluminum are believed to be Al^{+3}, $AlSO_4^{+}$, $AlOH^{+2}$ and $Al_6(OH)_{15}^{+3}$ and also small amounts of $H_2AlO_3^{-}$ and $AlH_2PO_4^{+2}$ (Richburg and Adams, 1970). The form of aluminum ions present is difficult to determine. The work of Coleman and Harward (1953) and others which indicated that acid clays were aluminum saturated, not hydrogen saturated, led to considerable interest in the effects of aluminum on plant growth.

Effects of Aluminum on Plant Growth

The toxicity of aluminum to plants was first shown by Vietch in 1902. The toxicity to plants of soluble aluminum from acid soils was shown by Abbott, Connor and Smalley in 1913 who state, "the unproductive-

ness of the soil in question was due principally to the presence of soluble aluminum salts or more fundamentally to the lack of basicity which permits them to exist". Morse (1915) suggested the effect of liming is "to improve the soil environment" rather than increase the calcium supply. In 1915 Ruprecht studied soils which had become unproductive from 25 years application of ammonium sulphate. He isolated soluble iron and aluminum from these soils. He experimented with culture solutions and suggested that with red clover above 40 ppm aluminum is toxic and iron is toxic above 4 ppm. Calcium carbonate could alleviate this toxicity but calcium sulphate did not and Ruprecht concluded this was not a calcium deficiency but was an aluminum toxicity. He also noted that the effect of aluminum "was the arresting of development of cells in the growth areas of root tips". The idea that aluminum was the toxic factor in acid soils was further expressed by Hartwell and Pember in 1918 and later by Pierre in 1931. Schmehl, Peech, and Bradfield (1950) varied levels of hydrogen, calcium, and aluminum in acid soils by adding $CaSO_4$, H_2SO_4, and $Al_2(SO_4)_3$. They concluded significant crop damage was related to the effect of aluminum ions in soil solution. Ruprecht (1915) showed that aluminum is the main factor reducing crop yields on acid soils. Despite further work on soil acidity it remained until the past five years for measurements of soluble aluminum to be used in determining the toxicity of an acid soil to plants, or in determining lime requirements.

As previously mentioned Lance and Pearson (1969) found short exposures to low concentrations of aluminum reduced the uptake by plant roots of water, calcium, magnesium, phosphorus, and nitrate. Most plants which suffer from aluminum toxicity show symptoms similar to phosphorus deficiency. However, in all plants root development is more restricted

by aluminum toxicity than by phosphorus deficiency (Jackson, 1967). Cheng, Bourget, and Ouellette (1971) showed that aluminum uptake is favored by cool temperatures and dry conditions. Toxicities would be expected to be most severe under those conditions that favor uptake of aluminum. Toxic levels of aluminum and soluble manganese combined may result in a moderating effect on aluminum toxicity.

Mn solution (toxic) + Al results in decreased yield;

Al solution (toxic) + Mn usually results in increased yield.

Jackson (1967) reports aluminum toxicity is most severe when an ammonium source of nitrogen is used rather than a nitrate source of nitrogen.

Reeve and Sumner (1970) obtained good correlations on exchangeable (0.2M NH_4Cl) aluminum extracted from South African oxisols and lime response of trudan (*Sorghum sudanense*). Adams and Pearson (1967) got good correlations of exchangeable aluminum with growth of alfalfa (*Medicago sativa*), barley (*Hordeum vulgare*), and soybeans (*Glycine max*). Hoyt and Nyborg (1971), working with barley, rape (*Brassica campestris*), and alfalfa, obtained a good correlation with yield increases obtained by liming acid soils and the amount of 0.01 molar calcium chloride soluble aluminum extracted from the unlimed soil. Thus it appears well established that on most acid soils crop damage of aluminum-sensitive crops such as alfalfa, barley, rape and sorghum is proportionate to the amount of aluminum present in the soil solution.

Effect of Aluminum Toxicity on Cell Division and DNA Synthesis

There is evidence to suggest that aluminum may bring about changes in cell division. Clarkson (1966) found that *Agrostis tenuis*, grown in solutions containing 10^{-3}M aluminum sulphate, showed failure of main

roots to develop, resulting in formation of lateral roots which also failed to develop. This suggests aluminum inhibits development of the root apex and may have an effect on the meristematic region. Clarkson (1968), working with nutrient culture solutions, found that onion roots showed a 50 per cent reduction in growth rate after three hours exposure to aluminum and this reduction of growth was present 36 hours after the roots had been transferred to fresh water solutions. Six hours exposure to 10^{-3}M aluminum sulphate solutions resulted in total stoppage of growth. It seems that the time of mitotic cycle in onion roots is about 18 hours and the S stage (interphase which occurs prior to formation of distinct chromosomes) involving DNA[1] synthesis is about ten hours. Clarkson (1968) suggests that the mechanism of aluminum inhibiting cell division is blockage of DNA synthesis during the S stage.

Other work by Sampson, Clarkson, and Davies (1965) showed the effect of aluminum on DNA formation in barley roots. They found that the length of treatment of roots with a 10^{-3}M $Al_2(SO_4)_3$ solution progressively decreased the number of root cells entering prophase, until after 24 hours no roots entered prophase. A similar pH of nutrient solution (4.5) --- without added aluminum --- did not alter the rate of cell division.

Barley roots contain low molecular weight (2.5×10^5) metabolically labile DNA with about 51 per cent guanine + cytosine, and high molecular weight (5×10^6) metabolically stable DNA with about 42 per cent guanine + cytosine. Sampson, Clarkson, and Davies (1965) believe that the high molecular weight DNA is the genetic DNA. They studied roots from aluminum treated plants where mitotic division had stopped and

---

1 deoxyribonucleic acid

found that both aluminum treated and growing untreated roots incorporated ^{32}P. However, the newly synthesized DNA of the aluminum treated roots was found to be metabolically labile in both the high and low molecular weight fractions. They found the aluminum treated roots had a percentage of guanine + cytosine in the low and high molecular weight DNA of 51 per cent and 53 per cent respectively. When the high molecular weight DNA from the aluminum treated roots was rendered single stranded (by heating and cooling) it was found to be composed of low molecular weight DNA which contained the ^{32}P label. They concluded that one of the effects of aluminum was to block production of genetic DNA but some of the low molecular weight, nongenetic DNA formed a hybrid with the genetic DNA. It appears that aluminum disturbs cell division much more than it disturbs metabolism.

Effect of Aluminum Toxicity on Nutrient Uptake and Metabolism

Interactions between aluminum and phosphorus on cell walls were described by Clarkson (1967). He found that roots, pretreated with aluminum, showed increased adsorption of phosphorus, but most of this phosphorus was on the surface of the root in an exchangeable inorganic form. He reported that aluminum was firmly bound to cell wall material and its adsorption was independent of temperature. He believed aluminum may be adsorbed by free carboxyl groups on polygalacturonic acids in the middle lamella. Aluminum is also known to form strong cross linkages with pectin. Clarkson (1967) believed that the aluminum on the surface of the root forms inorganic aluminum phosphates, thus reducing the availability of phosphorus to the plant.

Randall and Vose (1963) believe aluminum stimulates the metabolic

uptake of phosphorus, but this phosphorus is precipitated throughout the plant as aluminum phosphates, resulting in the plant having symptoms of phosphorus deficiency. This is not in agreement with the findings of Clarkson (1967), who believes that the increased phosphorus content is due to chemical precipitation of aluminum phosphates in plant roots. In Clarkson's opinion the reactions between aluminum and phosphorus are: (1) nonmetabolic and occurring at the cell or root surface and in free spaces within the root; (2) metabolic and occurring inside the cell, perhaps in the mitochondria and affecting phosphorylation of hexose sugars. In Clarkson's view the nonmetabolic reaction may reduce the amount of phosphorus available to a plant, thus bringing about a phosphorus deficiency.

Aluminum toxicity also affects general metabolic rates. Woolhouse (1968) found that aluminum toxicity reduced the activity of ATP-ases and acid phosphatases. Bonner (1965) reports that acid phosphatases are present in abundance in the short epidermal cells which develop into root hairs and that little acid phosphatase is present in the longer epidermal cells which do not form root hairs. Clark and Brown (1973) show that an aluminum-tolerant maize variety showed less reduction of activity of the enzyme acid phosphatase than did an aluminum sensitive variety. It seems that the enzyme acid phosphatase must play a part in root hair formation and then aluminum, inhibiting this enzyme, is one of the factors contributing to poor root hair development of plants in soils with a high content of soluble aluminum. Clarkson (1968) used root material pretreated with aluminum sulphate as contrasted to untreated control. He measured rates of incorporation of ^{32}P into the tissue and analyzed the products. Pretreatment with aluminum sulphate, when contrasted to the control, increased the UTP[1], ATP[2], and ADP[3] content, but decreased hexose -P and total or-

ganic -P and considerably increased the inorganic -P. Clarkson (1968) believed that this drop in respiratory activity, as shown by failure of formation of organic phosphates, is not related to mitotic cessation in aluminum treated roots. Mitotic failure occurs after 6 to 12 hours treatment with aluminum solutions, while respiratory reduction only occurs after 24 hours treatment with aluminum solutions.

Mechanisms of Resistance to Aluminum Toxicity

Foy, Fleming, Burns, and Armiger (1967) found that aluminum sensitive varieties of barley have higher cation exchange capacities on the root surfaces than aluminum tolerant varieties. They believe this higher cation exchange capacity may be the reason aluminum sensitive varieties of barley accumulate more aluminum near the root surface. The above authors state a higher root CEC[4] may result in greater adsorption of cations relative to anions, greater release of H^+ ions, a lower pH in the root microzone, increased solubility of aluminum, and therefore an increased uptake of aluminum ions by the root. Also the higher CEC may result in a greater uptake of aluminum ions because of exchange sites for cations and because of an increased selective binding of trivalent ions over monovalent and divalent ions according to the Donnan principle. Foy, Fleming and Gerloff (1972), working with snapbeans (*Phaseolus vulgaris*), showed that an aluminum sensitive variety had reduced uptake of calcium and phosphorus as measured in root nuclei, root mitochondria, and stem exudates and reduced levels of calcium in root cell walls. They suggest the measurement of the uptake of calcium under high aluminum conditions is a good measure of aluminum tolerance.

---

1 uridine triphosphate; 2 adenosine triphosphate; 3 adenosine diphosphate
4 cation exchange capacity

Dodge and Hiatt (1972) suggest an ion imbalance is created by selective uptake of anions and cations. They suggest aluminum sensitive varieties show lower anion uptake (nitrate) and greater cation uptake (potassium) than aluminum tolerant varieties. However, they do not report the significant differences in calcium uptake which Foy, Fleming and Gerloff (1972) found to be the major difference between aluminum tolerant and sensitive varieties and they do not record phosphorus uptake.

Resistance to aluminum toxicity on acid soils may be the same mechanism as sensitivity to iron chlorosis on alkaline soils (Grime and Hodgson, 1968). Grime and Hodgson found that the same species of plants which developed iron chlorosis also showed considerable aluminum tolerance. They believe the mechanism may be a chelation, which is the same for both iron and aluminum, and which removes soluble ions from solution and prevents them from entering the plant's metabolic system. This results in a plant variety suffering from iron deficiency on alkaline soils where the solubility of iron is low. This seems feasible and is in agreement with observations of McKenzie (1970), who found organic additives to the soil, without changing the soil pH, reduced the level of soluble aluminum in soil solution and improved the growth of alfalfa.

Manganese

Manganese becomes increasingly soluble in the soil at about the same pH (4 to 5) as aluminum (Blume and Schwertman, 1969). However, large amounts of soluble manganese may be found at pH values above 5 on wet soils or soils high in aluminum. It is toxic to plants at high levels and results in browning of roots and a speckled appearance developing on the older leaves. Jackson (1967) reports plants subjected to toxic levels of manganese show higher activities of isocitric dehy-

drogenase and malic enzyme in leaf extracts. This is different from toxicity of aluminum or iron where activities of these enzymes are depressed. Manganese deficiency, on the other hand, reduces the Hill reaction and causes disruption of chloroplast lamellae structure. It may also be associated with DNA and ribosome function.

Manganese uptake and distribution is very complex as it is influenced by many other ions. High levels of manganese under certain light conditions may depress iron uptake, causing iron deficiency (DeKock and Inkson, 1962). Hoyt and Nyborg (1971a) obtained a good correlation between the manganese content of plants and 0.01M $CaCl_2$ soluble manganese in the soil. However, they did not get good correlations between soluble manganese in the soil and crop yields. Pearson and Adams (1967) report that in southeastern USA toxic levels of manganese are mostly found on soils developed on limestone residuum and loess. It appears that manganese toxicity does occur on acid soils. However, it does not occur as frequently as aluminum toxicity. Other chemical factors may increase or reduce the effect of manganese toxicity. Foy, Fleming and Schwartz (1973) point out that the factors in a plant which control resistance to aluminum toxicity are quite different from those that control resistance to manganese toxicity and hence the term acid tolerant variety should not be used.

Iron

Iron may become toxic in acid soils, but since $Fe(OH)_3$ becomes soluble at a slightly lower pH than manganese and aluminum it is not often a problem. Cheng, Bourget, and Ouellette (1971) showed that uptake of iron is favored by high temperatures and wet conditions. Iron toxicities are reported in rice paddies by Ota and Tanaka (1960) when the paddies were at low oxidation-reduction potentials. Iron toxicities do not appear

to occur often other than in rice paddies or submerged soils.

Phosphorus

The availability of soil phosphorus is low in acid soils. Aluminum and iron phosphates form and have limited solubility under low pH conditions. Under acid conditions plants absorb phosphorus but suffer phosphorus deficiency because of precipitation of iron and aluminum phosphates on cell walls. Because of this phosphorus precipitation, plants grown on acid soils often show abnormally high phosphorus values for root tissue and sometimes for leaf tissue. Many cases are reported by Jackson (1967) where additions of phosphorus to soil help overcome toxic effects of aluminum. Jackson reports phosphorus additions to an acid soil do not alter the aluminum content of plant tops but serve to increase the aluminum content of plant roots. However, Estrada and Cummings (1968) report large phosphorus additions decreased the aluminum content of corn (*Zea mays*) foliage. Long, Langdale and Myhre (1973), working with oats (*Avena sativa*) and millet (*Setaria italica*), and Estrada and Cummings (1968), working with corn, found that large phosphorus additions were more important than lime additions or reducing toxic levels of aluminum in alleviating acid soil infertility. Estrada and Cummings (1968) attribute the yield increases from phosphorus to reduced aluminum uptake rather than increased phosphorus uptake.

McCormick and Borden (1972) developed a technique of staining roots which showed phosphorus accumulations. Roots which received aluminum and phosphorus showed accumulations of phosphorus at the root surface and in the epidermal and cortical regions around the root tip. The aluminum phosphates appeared to be associated with the cell wall and outside

the cytoplasmic membrane. Plants which received only phosphorus showed no concentrations of phosphorus. This substantiates work of Clarkson (1968) and others who have stated a main effect of aluminum toxicity is the precipitation of phosphorus.

Nitrogen

Acid soils inhibit nitrification and have nitrogen chiefly in the form of ammonium. When plants absorb an ammonium ion, this results in a release of a hydrogen ion and an increase of acidity in the zone adjacent to plant roots. This increased acidity solubilizes soil aluminum and may intensify aluminum toxicity damage to crops. Some plant species are not able to efficiently utilize ammonium under acid conditions. Sheat, Fletcher and Street (1959) found that tomatoes could effectively utilize ammonium at pH 7, but could not utilize ammonium at pH 4.5. Use of heavy applications of ammonium fertilizers on soils with pH 5 to 6 may result in depression of the soil pH by the nitrification process, thus causing further soil acidity problems. Under natural conditions ammonium is the main form of nitrogen present in acid soils but it is an unsatisfactory form of nitrogen for many plant species. Legumes, such as alfalfa and clover show reduced or no fixation of nitrogen when grown under acid conditions.

Magnesium

Magnesium deficiency is most frequently found on acid, sandy soils (Pearson and Adams, 1967). Moore, Jacobson and Overstreet (1961) showed that barley roots' uptake of magnesium was severely depressed below pH 5 and the roots lost magnesium below pH 4. Toxic levels of aluminum depress magnesium uptake. The presence of a high calcium to magnesium ratio depresses magnesium uptake. Liming magnesium deficient

acid soils with a calcium lime may aggravate the problem. Presence of high levels of ammonium or potassium will also create a magnesium deficiency. Magnesium deficiency results in failure of plants to synthesize protein and to manufacture chlorophyll. Magnesium deficiency is not common but is usually found on acid soils which have a magnesium saturation of less than five per cent of the exchange capacity.

Molybdenum

Acid soils show adsorption of molybdenum anions to clays and oxides of iron and aluminum. This results in a soil which does not supply adequate molybdenum for plant growth. Liming results in an increase of water soluble molybdenum. Molybdenum deficiency impairs the ability of a plant to convert nitrate to nitrite. According to Ivanova (1973) the nitrate reductase enzyme contains molybdenum and flavin, a molybdenum flavoprotein. Plants supplied with ammonium nitrogen, according to Hewitt and Grundy (1970), can grow normally without molybdenum. However, uptake of ammonium increases the acidity in the plant root zone. Molybdenum is also believed to be essential for nitrogen fixation bacteria to fix nitrogen in root nodules. However, its exact function is not known. Molybdenum deficiency is a problem which occurs most frequently with legumes on acid soils. It can usually, but not always, be overcome by liming.

Boron

The availability of boron is decreased when acid soils are limed. A lime induced boron deficiency is most frequently found on sandy soils low in organic matter.

Micro-organisms

Nitrogen fixation by microbial associations with legumes is greatly reduced on acid soils. Alfalfa rhizobia are the most sensitive rhizobia to soil acidity and their ability to fix nitrogen is reduced below pH 6 (Penney, 1973). Jackson (1967) reports that nutrient culture work with rhizobia shows them to be more sensitive to hydrogen ion toxicity than most higher plants. As mentioned earlier, molybdenum deficiency on acid soils is often a reason for failure of proper nodulation. *Nitrosomonas* and *Nitrobacter*, the two nitrifying organisms, are both quite sensitive to high acidity. Jackson (1967) reports an increase in mineralization of organic phosphorus when acid soils were limed. Sulphur oxidation organisms may be responsible for production of the acidity of many of the acid soils in Alberta and northeastern British Columbia (Clark and Green, 1964). The microbiological population of acid soils is different from more neutral soils and this population may not only be a cause of the soil acidity, but be part of the problem of reduced growth on acid soils.

Subsoil Acidity

There has not been a great deal of work done to show the effects of subsoil acidity on crop yields. Rios and Pearson (1964) used cotton (*Gossypium hirsutum*) grown in a neutral surface soil with their lower roots extending into a nutrient culture solution. They found the phosphorus level in the solution did not affect root development. Calcium was required in the solution for adequate root development. Aluminum concentrations above 1 ppm killed all roots, however it did not affect top growth. Manganese did not reduce root or top yield until it exceeded

90 ppm. However, the manganese from the nutrient solution was readily absorbed and translocated upward. This experiment suggests that the presence of relatively high levels of soluble aluminum in acid subsoils can result in the failure of plant roots to develop normally despite surface applications of lime. Other experiments of Rios and Pearson (1964) with cotton and sudangrass (Sorghum sudanense) show that an acid subsoil results in less water uptake from the subsoil and a lower subsoil root yield than a limed subsoil. Growth of soybeans (Glycine max) tops and roots was only very slightly affected by liming the subsoil.

The liming of surface soils usually has very little effect on subsoil acidity due to the slow downward movement of lime. Reeve and Sumner (1972) worked with acid oxisols from Natal. These soils had a high pH dependent CEC and resisted pH change and lime movement. These soils also had about 0.5 meq/100 g of calcium in the subsoil which led the authors to believe this would restrict root development. Heavy applications of lime to the plow layer did not alter the pH below 45 cm in leaching trials or in the field 14 years after the lime was applied. However, the authors found 18 m tons/ha of dolomitic lime plus 4 m tons/ha of gypsum greatly increased the downward movement of calcium as compared to the dolomitic lime alone. However, this downward movement of calcium was obtained at the expense of a loss of magnesium from the profile. Other studies by Pearson, Abruna and Vincente-Chandler (1962) have suggested using an acid nitrogen fertilizer like ammonium sulphate to effect downward movement of calcium. However, this practice would improve crop growth only if the acidity problem was a calcium deficiency and it would not aid crop growth if the problem was aluminum toxicity.

Table 1. Yields of Alfalfa as Related to Rates and Placement of Limestone.

Rate of limestone lb/acre	Depth of placement in inches	Yield over five years in lb/acre
4000	0-3	20,409
4000	0-6	16,473
8000	0-6	31,709
8000	0-12	35,419
16000	0-24	35,735

Most researchers have reported little increase in crop yield from lime applications to the subsoil. Longnecker and Merkle (1952), with greenhouse studies, obtained maximum yields of clover from liming the top three inches of pots, but noted an acid subsoil restricted root extension into the subsoil. Lathwell and Peech (1965) carried out field trials with depths and rates of liming. They concluded, "This experiment shows conclusively when small amounts of limestone are used higher alfalfa yields may be expected when the limestone is incorporated into the top three inches of soil. When large amounts of limestone are applied, the depth of liming has relatively little effect on yield even though the rate of limestone application per unit volume of soil may vary widely." However, their data do not substantiate this conclusion. An excerpt from their data is given in Table 1. The above data indicates a good response to increasing rates and depths of lime applications when the lime was incorporated to 12 inches. Barber (1967) cites five other authors who obtained no effect on crop growth from subsoil liming. Hourigan, Franklin, McLean and Bhumbla (1961) state that on the basis of greenhouse

experiments, surface liming is the major factor providing improvement of crop growth on acid soils. Results of the greenhouse experiments cited do not mention if any moisture stress was placed on the plants. It is evident if moisture and nutrients are adequate plants can be grown successfully in a small volume of soil. Results of field experiments with subsoil liming will also depend on the rainfall. If rainfall is heavy, gains from subsoil liming will be small. The authors of the best documented experiment on field subsoil liming (Lathwell and Peech, 1965) came to the questionable conclusion that subsoil liming did not help alfalfa growth.

It appears subsoil acidity does reduce the root development of plants and it does reduce the effective volume of soil from which plants can draw water and nutrients. Deficiency of calcium may be a problem in root penetration in acid subsoils. Phosphorus is quite mobile within the plant and is not a problem to root penetration of acid subsoils if it is present in sufficiently high quantities in the topsoil. Plow layer lime applications do not show much downward movement with time under most soil and climatic conditions.

Summary

Retardation of growth of plants on acid soils is most frequently caused by toxic levels of soluble aluminum. Manganese toxicity and sometimes iron toxicity may be a problem on acid soils. Calcium deficiency is seldom a cause of poor growth on acid soils, but a major effect of aluminum toxicity is to restrict uptake of calcium, thus reducing plant growth. One of the first effects of toxic levels of aluminum is to reduce water uptake by plants, also reducing plant growth.

Aluminum toxicities result in the plant developing phosphorus deficiency. Aluminum toxicity can be overcome by liming to reduce the solubility of aluminum or by large applications of phosphorus which cause the precipitation of aluminum phosphates in the soil and also on root walls and root cellular membranes. Hydrogen ion toxicity is seldom a problem to higher plants on acid soils because it requires a lower pH for toxicity than aluminum, manganese, or iron. Nitrification is inhibited by acid conditions so ammonium nitrogen levels are higher than nitrate nitrogen in acid soils. Uptake of ammonium nitrogen by plants on acid soils increases the acidity in the root environment. In acid soils nitrogen fixating bacteria on legumes do not grow well or effectively fix nitrogen.

The effect of acidity on plant growth varies depending on the toxic agent involved. Aluminum toxicity results in reduced respiration and failure of mitotic division. Manganese toxicity results in very high activities of isocitric dehydrogenase and reduced Hill reaction rates. The improvement of low crop yields on acid soils requires liming or high phosphorus applications. For field use the cost of high applications of phosphorus is not practical. Tolerant species or varieties of crops can be used, but the tolerant species or varieties are usually only tolerant to one factor of acidity damage. An aluminum tolerant crop may not be tolerant to manganese toxicity.

Subsoil acidity appears to limit root development due to low calcium uptake in the acid zone and the failure of calcium to move downward in plant roots. Phosphorus is quite mobile within plants and surface applications of phosphorus do supply sufficient phosphorus for root development. Movement of lime downward in acid soils is very slow even

in moist subtropical conditions. The limited root development in acid subsoils restricts the amount of moisture a plant can obtain in dry seasons and thus reduces plant growth.

MATERIALS AND METHODS

Field Experiments

The field experiments consisted of a series of subsoil liming plots which were set up to determine the effect of subsoil acidity on crop growth under field conditions. Plots were set up at three locations in the fall of 1970 and spring of 1971 and two further sites in the spring of 1972. Legal locations, chemical analyses for the sites, and rates of lime added are given in Appendix I. These sites were chosen because they represented varying degrees of subsoil acidity and they were widely dispersed, which hopefully would provide a variety of climatic conditions. The first site, prepared in the fall of 1970, was near Silver Valley, Alberta on an extremely acid Humic Eluviated Gleysol soil of the "Josephine" series. Treatments applied were:

(1) dug to 12.5 cm; limed to 12.5 cm;

(2) dug to 50 cm; no lime;

(3) dug to 50 cm; limed to 12.5 cm; and

(4) dug to 50 cm; limed to 50 cm.

The purpose of treatments (1) and (3) was to determine whether deep digging had an effect on plant growth. Treatments (2) and (3) were designed to show if there was a response from surface liming. Treatments (3) and (4) were designed to show the effect of surface liming as compared to surface and subsoil liming. The experimental design was a Randomized Complete Block with four treatments and four replicates. The plots of the first treatment were dug to 12.5 cm. The plots of the last three treatments each consisted of a pit 50 cm deep and .61 meters wide by 2.44 meters long. Each plot had the soil removed in three layers:

0-12.5 cm, 12.5-25 cm and 25-50 cm and the soil was broken up with hand rakes and returned in the same order. Where lime was required, it was added in the form of $Ca(OH)_2$ and mixed with the soil at a rate sufficient to bring the soil up to pH 6.5. A cribbing made of 1 cm plywood .61 meters wide by 2.44 meters long was placed in each hole. The cribbing was 40 cm deep in the case of the deep holes and 12.5 cm deep in the shallow holes. The cribbing was installed with it about 2 cm above normal ground level. In each hole a partition was placed which divided it in half to provide two plots, each .61 meters wide by 1.22 meters long. In the spring of 1971 similar plots were installed at Bessborough, British Columbia on a Grey Solod of the "Alcan" series and at Plamondon, Alberta on an Orthic Grey Luvisol of the "Grandin" series. These represented sites of fairly high acidity levels. The treatments on these two sites were:

(1) dug to 12.5 cm; no lime;

(2) dug to 12.5 cm; limed to 12.5 cm;

(3) dug to 50 cm; limed to 12.5 cm; and

(4) dug to 50 cm; limed to 50 cm.

At these sites the unlimed plot was only dug to 12.5 cm. It was hoped by these treatments to separate the digging effect from the liming effect. These sites were also limed with $Ca(OH)_2$ at a rate estimated to be sufficient to bring the soil pH up to 6.5.

These plots were seeded in the spring of 1971 with Ladak alfalfa in the south end of each box and Galt barley in the north end. These were two varieties which had been shown to be sensitive to aluminum toxicity. Four rows, each 15 cm apart, were seeded in each plot. In the

spring of 1971 and again in 1972 the plots were fertilized with:

NH_4NO_3 at 112 kg N/ha;

Ca_3PO_4 at 89.6 kg P/ha;

K_2SO_4 at 67.2 kg K/ha;

Borax at 1.12 kg B/ha;

NH_4MoO_4 at 0.056 kg Mo/ha.

The fertilizer application was mixed into the top three centimeters of soil in the spring. In the case of second year growth of alfalfa, the fertilizer was broadcast on the surface in the spring. Later in the summer the plots all received an additional broadcast application of 56 kg N/ha.

In the spring of 1972 two further sites were prepared. These were at Evansburg, Alberta on a Dark Grey Luvisol of the "Macola" series and at Valleyview, Alberta on a Grey Solod of the "Donnelly" series. They represented acid soils which had only moderate amounts of soluble aluminum. At these two sites holes were .61 meters wide and 1.5 meters long and no partition was used to divide the plots. Treatments were similar to those at Bessborough and Plamondon. The plots at these two sites were limed with $CaCO_3$ at a rate estimated to bring the soil pH up to 6.5, fertilized in a manner similar to the previous plots, and seeded with Galt barley.

Harvests were taken of alfalfa in the fall of 1971 and during early July and late August of 1972. Barley dry matter was harvested at three sites in 1971 and five sites in 1972. Dry matter yields were recorded as 1000 kg/ha. Harvests were taken of alfalfa and barley roots in the plots that were dug and limed 50 cm and the plots that were dug

50 cm, but limed only 12.5 cm. The plots were cored with a coring truck using a 5 cm coring tube placed directly over the row. Three cores were washed and screened to recover roots. Moisture determinations were made on subsoil samples from the plots that were dug and limed to 50 cm and the plots that were dug to 50 cm, but limed only to 12.5 cm.

Yields of top growth were subjected to analysis of variance. Differences between means were determined by an LSD method developed by Waller and Duncan (1969). LSD values were determined for a type 1 to type 2 error-seriousness or error-weight ratio of 100:1. (Type 1 error = probability of rejecting a true hypothesis; type 2 error = probability of accepting a false hypothesis). This LSD method was used in preference to Duncan's Multiple Range Test and other types of LSD procedures. Considerable discussion has occurred on whether the significance level α on which differences are measured should be based on a comparisonwise approach or on an experimentwise approach. In a comparisonwise approach the LSD value does not increase with n, the number of treatments involved. If n is large, this gives a high probability of finding a significant difference simply due to the number of treatments involved. In an experimentwise approach the LSD value increases rapidly with n. This reduces the power of the test to measure differences. The LSD value of Waller and Duncan is a blend of these two approaches. It shifts in relation to the F value and in relation to the number of treatments and error degrees of freedom. For F values above 2.5 the LSD value changes very slowly with larger values of n. For F values below 2.5 the LSD value increases rapidly with increasing values of n. The level of 100:1 error-seriousness ratio used is analagous to a 5 per cent significance level of other tests.

Soil pH, soluble aluminum and manganese, and extractable aluminum and manganese were determined on all samples. Also extractable calcium, magnesium, and sodium were determined. The details of analyses are given in the Chemical Analyses section.

Chemical Analyses

Soil pH was determined on a mixture of 2.5 parts water and one part soil. The sample was stirred for one half hour and allowed to settle for one hour. The hydrogen electrode was placed in the sediment, the KCl electrode in the supernatant solution. For soluble aluminum and manganese determinations, a mixture of one part soil to two parts 0.02M $CaCl_2$ solution was shaken for one hour. It was filtered with suction on a "Whatman" no. 42 filter paper. Separation was also done by centrifugation for ten minutes at 2500 g and filtration by gravity on a "Whatman" no. 42 filter paper. For exchangeable aluminum and manganese a mixture of one part soil to five parts 1M KCl was shaken for a half hour. The extraction was similar to that used for soluble aluminum and manganese. Aluminum was determined by the aluminon procedure as outlined by Hsu (1963) except that the dilution with water was made before instead of after heating. Thioglycolic acid was added to inhibit iron interference (Chenery, 1948). For the field survey samples, aluminum and some manganese solutions were determined by atomic absorption analysis of similar extracts. In other cases manganese was determined by oxidation with trisodium paraperiodate in the presence of H_3PO_4, according to the method outlined by Hoyt and Nyborg (1971a). Calcium, magnesium, and sodium were extracted by shaking a mixture of one part soil to 2.5 parts

1M KCl for half an hour and then determined by atomic absorption.

Greenhouse Experiment on Subsoil Acidity

A greenhouse experiment was set up involving ten acid soils selected from agricultural areas in various parts of Alberta. The purpose of the experiment was to determine what effect subsoil acidity had on growth of alfalfa. Treatments consisted of:

(1) unlimed topsoil, unlimed subsoil (nil/nil);

(2) limed topsoil, unlimed subsoil (lime/nil); and

(3) limed topsoil, limed subsoil (lime/lime).

Wooden boxes were prepared which were lined with polyethylene bags. The boxes were 13 cm by 13 cm and 28 cm deep. Each box received 12.5 cm of subsoil which had been ground to 2 mm size and 12.5 cm of topsoil, also ground to 2 mm size. The boxes were watered with distilled water to field capacity two weeks prior to seeding to provide time for the lime to react with the soil. The boxes were fertilized to provide nitrogen as NH_4NO_3 at 60 ppm, sulphur as Na_2SO_4 at 10 ppm, boron at one ppm, and molybdenum at 0.01 ppm. A solution of KH_2PO_4 was banded at 3 cm depth to provide potassium at 25 ppm and phosphorus at 20 ppm. Alfalfa was planted in holes 1.3 cm deep, covered with Ottawa sand, and watered several times daily until emergence was complete. Plants received 16-18 hours light daily and temperatures ranged from 14°C to 32°C. The boxes were watered to field capacity with distilled water. Waterings were scheduled to provide slight drought between waterings and to bring the soil to field capacity at the time of watering. An extra application of nitrogen was provided to all plants during growth. After three and a half months

the alfalfa was harvested and weights of dry matter of tops were recorded. The soil was washed from the roots and root weights were recorded for topsoil and subsoil. The soils were analyzed before and after growth of plants for 0.02 M $CaCl_2$ soluble aluminum and manganese and 1M KCl exchangeable aluminum and manganese. Soil pH was recorded at the start of the experiment, on the moist soil after harvest, and on the dried soil later. Correlations were made between chemical factors of the soil and growth ratios of top growth and root growth on limed and unlimed pots.

Growth Cabinet Experiment with Phosphorus

An experiment was set up to show the effect of high applications of phosphorus on root penetration into an acid subsoil. The soil for this experiment was a slightly acid Grey Solod of the "Lowater" series. Treatments were: (1) no treatment to topsoil and subsoil;

(2) limed topsoil and limed subsoil;

(3) phosphorus added to topsoil, no treatment to subsoil;

(4) phosphorus added to topsoil and subsoil at rates of 150 ppm phosphorus.

One of the aims of this experiment was to develop a type of container which could be used for growth experiments, which was water tight and did not require a polyethylene bag. A polyethylene bag encouraged root development down the side of the container. Containers consisted of large wooden boxes, 13 cm by 13 cm by 31 cm deep, which were coated with cellulose acetate and polyvinyl chloride. Small boxes, 10 cm by 10 cm by 27 cm deep, were coated with latex cement and two 1360 cc (48 oz) fruit juice tins provided a cylinder 10.5 cm in diameter and 70 cm high. The

experiment was conducted in a growth cabinet cooled from the bottom to provide 15°C at the top of the containers and 9°C at the base of the containers. Lighting provided 16 daylight hours and 8 hours of darkness. Light was 1500 to 1800 foot candles at the leaf surface.

The containers received the following amounts of air dry soil ground to pass a 2 mm screen:

	topsoil in g	subsoil in g
large box	3100	3100
small box	1700	1700
tin cans	1850	1850

Fertilizers mixed with topsoils of all treatments were:

N as $NaNO_3$ at 80 ppm;

S as Na_2SO_4 at 20 ppm;

B as Borax at .5 ppm;

Mo as NH_4MoO_4 at .025 ppm; and

P and K as KH_2PO_4 at 25 ppm P and 31 ppm K, banded at 3 cm depth. In addition, the lime treated soils received $Ca(OH)_2$ mixed with the soil at a rate of .25 per cent $Ca(OH)_2$. The phosphorus treated soils received phosphorus mixed into the soil at a rate of 150 ppm, phosphorus applied as KH_2PO_4. The soils were seeded to Galt barley on August 28, 1971. On September 30 an additional application of 20 ppm nitrogen as $NaNO_3$ was made. The barley was harvested on November 2, 1971 and dry matter weights were recorded. The soils were washed and screened to recover the roots which were weighed. Dry matter yields were subjected to analysis of variance and treatment differences were measured by LSD (Waller and Duncan, 1969). Soluble aluminum, soluble manganese, and pH were determined on all soils.

Greenhouse Experiment with Temperature and Acidity of Subsoils

A greenhouse experiment was designed to determine if any interaction existed between root development of alfalfa grown on acid soils and soil temperature. The experiment was set up in a Factorial design with factors of temperatures, soils, and lime rates. Three soils were used representing low, intermediate, and high levels of soluble aluminum in the subsoil. Three levels of acidity were achieved on each subsoil by liming to remove all soluble aluminum, liming to reduce soluble aluminum, and no lime. Surface soils were limed to neutrality. The soils were placed in cylinders which consisted of two 1360 cc (48 oz) fruit juice tins which were joined by silicone sealant. This gave a cylinder which was 31 cm long and 13 cm in diameter. The inside of the cylinder was coated with a latex cement for one replicate and with an asphalt tar compound for the second replicate. Three temperatures were obtained by using three retail style wet type soft drink coolers. Two of the coolers were equipped with a 3°C differential thermostat. The third cooler was equipped with an aquarium heater.

Twenty four soil psychrometers were prepared according to a method of Dalton and Rawlings (1966) which was modified by Mayo (1970). These psychrometers were placed in the lower and upper halves of twelve cylinders. They provided a means of monitoring moisture losses and determining if sufficient water was being added at the top of the cylinders to replenish moisture losses in the lower part of the cylinders. Thermocouples were made to provide a means of directly reading the soil temperatures and of making temperature corrections on the psychrometer readings. Thermocouples were placed in the top and bottom of six cans.

The three soils used were: a Humic Eluviated Gleysol of the "Josephine" series, initial pH of the subsoil was 4.4; a Grey Solod of the "Alcan" series, initial pH of the subsoil was 5.2; and a Grey Solod of the "Alcan" series, initial pH of the subsoil was 5.1. The soils were ground to pass a 2 mm screen, limed to appropriate levels, and placed in the cylinders. Psychrometers and thermocouples were installed in some of the cylinders. The soils were watered to field capacity and allowed to sit for one week before seeding to Ladak alfalfa. Alfalfa was seeded in a similar manner as described in the Greenhouse Experiment on Subsoil Acidity. A fertilizer solution was mixed with the topsoil to provide:

80 ppm N as NH_4NO_3;

20 ppm S as Na_2SO_4;

.5 ppm B as H_3BO_4;

.025 ppm Mo as NH_4MoO_4.

Phosphorus and potassium were added as KH_2PO_4 to provide 50 ppm phosphorus and 62 ppm potassium. The KH_2PO_4 solution was banded at 3 cm depth. Air temperature was at 21°C day and night and the plants received 16 hours of light and 8 hours of darkness. After emergence of alfalfa was complete the soils were placed in three coolers which provided the following three subsoil temperatures of 8°C, 14°C, and 21°C. After six weeks, when the alfalfa was well established, the containers were watered to field capacity for several days in succession to bring the moisture level in the subsoils to near field capacity. The psychrometers were used to monitor the soils to determine if water had infiltrated to the subsoils. Then the pots were allowed to dry out until wilting was evident. Before watering, the pots were weighed and moisture losses recorded in order to

determine the effectiveness of root function in withdrawing water from the subsoil.

Tops were harvested after 76 days growth and dry matter yields recorded. The soils were washed and screened and topsoil and subsoil root yields were obtained. The top and root yields were analyzed by analysis of variance. Differences between means were determined by an LSD method of Waller and Duncan (1969). Soil pH, soluble aluminum and manganese, and extractable aluminum and manganese, and 1M KCl extractable calcium, sodium, and magnesium were determined on the subsoils.

Nutrient Culture Experiment

Growth of crops tolerant to the toxic factors present in acid soils is one method of managing acid soils. In Alberta most acid soils have aluminum as the major toxic factor limiting growth of cereals. In acid subsoils, aluminum toxicity is the major factor limiting root penetration. Liming subsoils is not at present economically feasible. Heavy phosphorus applications to overcome toxic levels of aluminum are also very expensive. Consequently, growth of aluminum tolerant varieties of crops is the best way to manage soils with acid subsoils. Barley is an aluminum sensitive cereal crop which is frequently grown in areas of central and northern Alberta where acid soils may be present. A method developed by Foy and Brown (1964) was used to separate aluminum tolerant from aluminum sensitive varieties.

Two preliminary trials were made with growth of barley and oat varieties in nutrient culture solutions. The third trial consisted of nine pails with three pails at each of three levels of aluminum and eight

Table 2. Composition of Nutrient Solution.

Chemicals used	Concentration	Chemicals used	Concentration
KNO_3	2 mM	$CuSO_4 \cdot 5H_2O$	.3 μM
$Ca(NO_3)_2 \cdot 4H_2O$	4 mM	$ZnSO_4 \cdot 7H_2O$	.8 μM
$MgSO_4$	2 mM	H_3BO_3	10 μM
$(NH_4)_2SO_4$	.5 mM	NH_4MoO_4	.1 μM
$NH_4H_2PO_4$	10 μM	NaCl	30 μM
$MnSO_4 \cdot H_2O$	2 μM	FeEDTA	10 μM

varieties of barley grown in each pail. The experimental design was a randomized complete block. The pails each contained 10.2 liters of solution. The nutrient solution used was that of Kerridge, Dawson and Moore (1971)(Table 2). The pH of the solution was checked daily and maintained at 4.0 by additions of dilute HCl and NaOH. Phosphorus concentrations were checked several times during the growth period and adjusted upward. Aluminum levels were initially 0, 4, and 12 ppm. An additional 1.5 ppm aluminum was added to the 4 ppm solution and 2.5 ppm aluminum was added to the 12 ppm solution. Nylon mesh screens covered the bottom of cylinders which were made from sections of 4 cm inner diameter polyethylene pipe. The pipe sections, 4 cm long, were mounted in an opaque acryllic plastic sheet which covered the top of each pail. Each pail was aerated by means of a glass tube with a porous bulb at the base. These tubes were connected to a manifold supplied with air at about 75 g /sq cm pressure. "Captan" fungicide was used to control growths of fungi on each pail. The eight barley varieties used were selected mostly from varieties used in northern Alberta. Galt and Olli barley, which were

aluminum sensitive and aluminum tolerant respectively were included. Volla, a new barley variety which has been recommended for Nova Scotia was included. The other varieties were Centennial, Conquest, Betzes, Bonanza, and Jubilee. The barley seeds were germinated on filter paper which had been watered with the appropriate nutrient solutions. After three days the seedlings were placed on the nylon mesh screens at the base of the polyethylene cylinders. After 13 days growth in the pails, the seedlings were harvested and lengths of roots and top growth were measured. Root lengths and top lengths were analyzed by analysis of variance and differences between means were determined by an LSD method of Waller and Duncan (1969).

A Field Survey on Subsoil Acidity

A field survey was undertaken to determine the approximate extent of areas which might contain appreciable subsoil acidity. With the help of a coring truck, samples were taken from cultivated fields in the Boyle-Lac La Biche area; the Evansburg-Whitecourt-Fort Assiniboine area; and in the Peace River region including Dawson Creek, Fort St. John, and Beaton River areas. A few samples were also collected from west central Alberta in the area from Buck Lake to Rocky Mountain House. General areas for sampling were chosen on the basis of previous known areas that showed acidity problems, and soil survey data that indicated soil series which might have acid subsurface horizons. In addition, T.A. Lord of the Federal Soil Survey in Vancouver provided some samples from the Peace River area in British Columbia.

Field samples were analyzed for pH. Those samples which had a

water pH below 6 were analyzed for aluminum and manganese. Analyses were done by atomic absorption on 0.02 M $CaCl_2$ extracts.

Cores were taken to 1 or 1.2 meters and depths of horizons were identified. For the presentation of data, results are shown for 0-15 cm, 15-30 cm, 45-60 cm, and 90-110 cm as it was believed this would give a good representation of those rooting zones which would be of most importance to crop production. Correlation coefficients and regression equations were determined for the relation of soluble aluminum to pH at the three depths mentioned above. Maps were prepared to show the location of areas where soluble aluminum occurred at toxic levels in subsoils.

RESULTS AND DISCUSSION

Field Experiments

Field plots with limed subsoils were installed at five sites to determine if subsoil liming would affect plant growth under actual field conditions. Ladak alfalfa and Galt barley were grown at three sites in 1971 and 1972 and Galt barley was grown at two additional sites in 1972.

The results (Tables 4, 5, 6, and 7) show that in all cases with barley and alfalfa some increases in yields took place in the plots dug and limed to a depth of 50 cm (deep limed), as compared to the plots that were dug to 50 cm, but limed only to a depth of 12.5 cm (shallow limed). These increases in yield were much larger with alfalfa, a deep rooted crop, than with barley, a more shallow rooted crop. At all sites barley and alfalfa showed from slight to large increases in yield on the plots that were dug and limed to 12.5 cm, as compared to the plots that were not limed. These increases in crop yields indicate there are benefits from subsoil liming in addition to the benefits obtained from liming the topsoil.

Weather records from the Government of Canada Department of Transport (Table 3) indicate that in the years of 1971 and 1972 rainfall was not normally distributed. The early part of the growing season in the years 1971 and 1972 was extremely dry. To overcome this drought and ensure uniform germination of crops, all sites were watered with about one inch of water either at the time of seeding or about one week after seeding in 1971 and 1972. After about the middle of June rainfall was unusually heavy. This resulted in flooding at the Plamondon site.

Table 3. Rainfall During the Growing Season near the Sites of the Field Plots.

Dept. of Transport Weather record site (Plot site)	Year	Rainfall in inches: April	May	June	July	August	September	Total
Dawson Creek (Bessborough)	1971	0.55	0.05	6.81	2.38	1.40	3.70	14.89
	1972	0.64	0.08	1.29	3.28	3.33		8.62
Blueberry Mt. (Silver Valley)	1971	0.95	0.17	6.01	2.94	1.29	2.54	13.90
	1972	0.15	0.22	2.03	4.84	3.16		6.40
Lac La Biche (Plamondon)	1971	0.43	*May 29 1.00	*June 29 4.50	*July 15 3.50	*Aug. 16 3.00	*Sept. 10 3.15	
	1972			3.97	4.06	2.45		10.48
Valleyview (Valleyview)	1972	0.42	0.75	5.03	2.79	2.51		11.50
Niton Junction (Evansburg)	1972	0.55	2.14	6.46	1.19	2.04		12.38
Beaverlodge (43 yr average)		0.87	1.50	2.01	2.31	1.92	1.87	10.48
Fort St. John (14 yr average)		0.87	1.07	2.12	1.94	1.81	1.14	8.95

* Department of Transport records are not available for all months at Lac La Biche, so from May to Sept., 1971, cumulative rainfall readings taken at the Plamondon plot site are shown for five readings.

Table 4. Dry Matter Yields of Barley and Alfalfa from Field Subsoil Liming Plots at Silver Valley, Alberta.

Treatment		Yield of crops, q/ha				
		Barley		Alfalfa		
Depth dug cm	Depth limed cm	Sept./71	Sept./72	Oct./71	July/72	Sept./72
12.5	12.5	6.02a⊕	6.00a	0.87ab	2.33a	5.35a
50	0	0.40b	1.03b	0.004c	0.01c	0.11c
50	12.5	5.48a	5.95a	0.673b	1.47b	3.52b
50	50	6.68a	6.10a	0.965a	2.39a	5.84a
F		35.6**	23.3**	17.7**	83.0**	17.3**
LSD		1.96	1.43	0.29	0.34	1.75

⊕ All those values which are not followed by the same letter are significantly different at an LSD value at a 100:1 error seriousness ratio according to the method of Waller and Duncan (1969).

** F value is significant at the 1% level of probability.

This heavy summer rainfall reduced the need for the crops to use subsoil moisture. In years with more normal rainfall distribution, such as shown for the average rainfall for Beaverlodge and Fort St. John (Table 3), the benefits of subsoil liming should be greater.

At the Silver Valley site all the plots with limed treatments showed greatly increased yields over the plots with unlimed treatments (Table 4). This was because the site was quite acidic and had soluble aluminum ranging from 58 ppm in the 0-12.5 cm layer to 94 ppm in the 25-50 cm layer. The plots that were dug and limed to 50 cm, when compared to the plots that were dug to 50 cm, but only limed to 12.5 cm, showed significant yield increases of alfalfa and smaller --- but not

significant (at the 100:1 error seriousness ratio) --- yield increases of barley. The summer of 1971 was wetter than normal and the summer of 1972 was extremely wet at this site. This accounts for the small difference in yields of barley between the plots that were deeply limed and the plots that were shallow limed. The plots that were dug and limed to a depth of 12.5 cm were included to determine the effects of digging by comparing this treatment to the plots that were dug to a depth of 50 cm and limed to a depth of 12.5 cm. However, in anticipation of settling occurring in the fall of 1970, deeply dug plots were mounded. An error in the spring of 1971 resulted in all the plots being levelled. Therefore a loss of 4 to 5 cm of limed topsoil occurred on the plots dug to a depth of 50 cm. As a result of the loss of topsoil at this site any comparison between the yields of the deeply dug plots and the shallow dug plots is not valid.

The soil at the Bessborough site was not as acid as the soil at Silver Valley, however it showed good responses to surface and subsoil liming (Table 5). For the two crops and the two years the plots that were dug and limed to a depth of 50 cm showed significant yield increases over the plots that were dug to 50 cm, but limed only to 12.5 cm. Also, for the two years the plots that were dug and limed to a depth of 12.5 cm showed significant yield increases of barley and alfalfa over the unlimed plots. This site also had abnormally heavy rainfall during the summers of 1971 and 1972. This reduced the moisture stress and the effect of the deep liming. Moisture data (Appendix II) for 1971 showed that when lime was applied to a depth of 50 cm there was less moisture at the 25-50 cm depths under both alfalfa and barley than when the soil was limed to a

Plate 1. The site of the field experiment at Bessborough, British Columbia in August of 1972.

Plate 2. A close-up of two plots at Bessborough, British Columbia, the plot on the left is dug to a depth of 50 cm, but limed to only 12.5 cm, and the plot on the right is dug and limed to a depth of 50 cm. Alfalfa after the first harvest is at the front of the plot and barley is at the back of the plot.

Table 5. Dry Matter Yields of Barley and Alfalfa from Field Subsoil Liming Plots at Bessborough, British Columbia.

Treatment		Yield of crops, q/ha				
		Barley		Alfalfa		
Depth dug cm	Depth limed cm	Sept./71	Sept./72	Oct./71	July/72	Sept./72
12.5	0	5.29c[⊕]	7.04c	0.78c	1.75b	1.80b
12.5	12.5	7.40ab	7.93b	1.18ab	2.59a	2.66a
50	12.5	6.28bc	7.07c	0.87bc	1.87b	2.11b
50	50	8.19a	9.30a	1.38a	2.86a	2.70a
F		3.67*	16.2**	3.12	6.32*	9.6**
LSD		1.82	0.75	0.25	0.65	0.41

⊕ All those values which are not followed by the same letter are significantly different at an LSD value at a 100:1 error seriousness ratio according to the method of Waller and Duncan (1969).

* F value is significant at the 5% level of probability.

** F value is significant at the 1% level of probability.

depth of 12.5 cm. Alfalfa was more effective than barley in using water from the 25-50 cm depth.

The Plamondon plot was situated in a poorly drained area and extremely heavy rainfall in June and July of 1971 resulted in some of the plots being flooded for several weeks. Again in the summer of 1972 some flooding occurred. The plots that were deeply limed suffered less damage from the flooding than the plots that were limed to 12.5 cm, perhaps due to better subsoil drainage. Harvest data were only collected on those plots where flooding damage was not serious (Table 6). Where statistics were performed alfalfa and barley showed significantly higher

Table 6. Dry Matter Yields of Barley and Alfalfa from Field Subsoil Liming Plots at Plamondon, Alberta.

Treatment		Yield of crops, q/ha				
		Barley		Alfalfa		
Depth dug cm	Depth limed cm	Sept./71	Aug./72	Oct./71	July/72	Aug./72
12.5	0	2.78	4.84c⊕	0.92	1.78	1.47c
12.5	12.5	5.77	6.49b	1.21	3.23	2.76ab
50	12.5	5.70	5.18bc	1.08	2.63	1.86bc
50	50	9.39	8.78a	1.52	3.91	3.19a
F		***	11.0**	***	1.57	5.42*
LSD			1.63			0.955

⊕ All those values which are not followed by the same letter are significantly different at an LSD value at a 100:1 error seriousness ratio according to the method of Waller and Duncan (1969).

* F value is significant at the 5% level of probability.

** F value is significant at the 1% level of probability.

***No statistics performed due to water damage from flooding destroying part of three reps.

yields on the plots that were dug and limed to a depth of 50 cm as compared to the plots that were dug to 50 cm and limed to 12.5 cm. For barley and alfalfa in 1971 and alfalfa in the spring of 1972 large real increases in growth appear to have occurred from deep liming and from surface liming as compared to the unlimed plots. For the fall of 1971 soil moisture data (Appendix II) for the Plamondon site showed less moisture present in the 25-50 cm depths in the plots that were deeply limed, for both barley and alfalfa. Similar moisture data were obtained

for alfalfa in 1972. Subsoil root yields for 1971 indicated more barley roots present below 25cm when lime was added to a depth of 50 cm. Alfalfa root data for September, 1971 showed similar root yields present at depth for both the shallow and deeply limed plots.

Barley was grown for only one year at the Valleyview and Evansburg sites. These two sites were selected because they represented areas which were only moderately acid, with levels of aluminum about 5 ppm at Evansburg and 7 ppm at Valleyview at the 25-50 cm depth. The results from the Evansburg site (Table 7) indicated significant yield increases for the plots that were dug and limed to a depth of 50 cm as compared to the plots that were dug to 50 cm and limed only to 12.5 cm. Shallow dug and limed plots had only a slightly larger yield of barley than unlimed plots. The site at Evansburg was very wet for part of the summer and

Table 7. Dry Matter Yields of Barley from Field Subsoil Liming Plots at Evansburg and Valleyview, Alberta.

Treatment		Yield of Barley, q/ha	
Depth dug cm	Depth limed cm	Evansburg Sept./72	Valleyview Sept./72
12.5	0	3.97b[♣]	7.03
12.5	12.5	4.29b	7.53
50	12.5	4.22b	6.55
50	50	5.62a	6.64
F		2.57	1.45
LSD		1.26	

[♣] All those values which are not followed by the same letter are significantly different at an LSD value at a 100:1 error seriousness ratio according to the method of Waller and Duncan (1969).

soil moisture levels were high at harvest time. No differences were observed in the subsoil moisture levels (Appendix II). The plots that were limed to a depth of 50 cm showed slightly more roots at the 37.5-50 cm depth than the plots that were limed to a depth of 12.5 cm (Appendix II). The Valleyview site (Table 7) showed high variability in yields between replicates. Though differences in yields of barley between treatments were not statistically significant, slight increases in yield did occur from surface liming as compared to the unlimed plots.

It was evident that deep liming increased the penetration of barley roots into the subsoil at all sites. The increased penetration was most evident on the Silver Valley, Plamondon, and Bessborough sites which had the highest levels of soluble aluminum in the subsoils (Figure 1 and Appendix II). The 37.5-50 cm layers of the shallow limed plots had almost no roots in those soils with the highest levels of aluminum, and only 36 per cent of the amount of roots that were present in the deeply limed plots at Evansburg and 52 per cent of the roots that were present in the deeply limed plots at Valleyview. The 25-37.5 cm layer of the deeply dug, shallow limed plots had reduced amounts of roots at all sites, except Valleyview. The 12.5-25 cm layer of the plots that were limed to 12.5 cm and dug to 50 cm in all cases had more roots than in the deeply limed plots. This can be explained by the branching of roots due to failure of root meristems to develop when they encounter toxic levels of aluminum. This results in a network of thick short roots forming in that zone. The top layer (0-12.5 cm) showed slightly more roots in most cases in the plots that were limed to a depth of 50 cm because of greater plant growth occurring on these deeply limed plots.

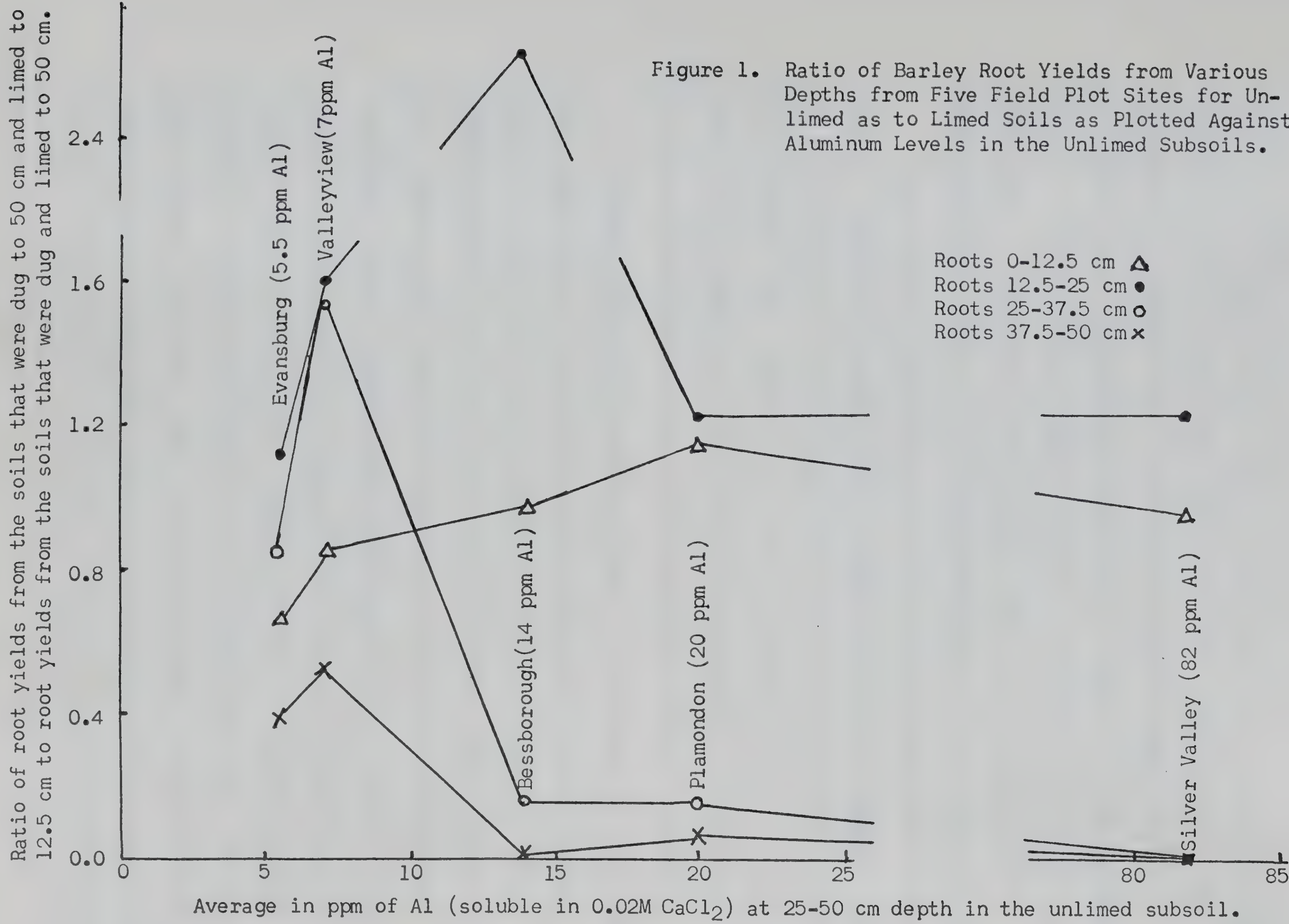


Figure 1. Ratio of Barley Root Yields from Various Depths from Five Field Plot Sites for Unlimed as to Limed Soils as Plotted Against Aluminum Levels in the Unlimed Subsoils.

Penetration of alfalfa roots into the subsoil was also increased by deep liming at the three sites where alfalfa was grown (Appendix II). Data in Appendix II indicate that soil moisture depletion under crops is a good index of root penetration and activity in subsoils. This increased removal of water at lower depths by barley and alfalfa roots in the deeply limed plots as contrasted to the shallow limed plots occurred despite heavy rainfall in excess of crop needs during part of the growing season.

Statistical analyses were not used on the soil moisture and root yields. Variability between plots was high, and with one degree of freecom for treatments and three degrees for error a very high F or t value was required to show significance. Using transformed values for root yields it was possible to show significant differences in many cases, but no one transformation seemed to be appropriate for all the data.

Subsoil liming does increase yields of acid-sensitive crops under field conditions in central Alberta and northeastern British Columbia. This is contrary to the views of Lathwell and Peech (1965) and other authors previously mentioned. The effect of subsoil liming appears to be on increased root penetration resulting in moisture being obtained from deeper depths. Lathwell and Peech used alfalfa in subsoil liming experiments and may not have separated the effect of nitrogen fixation on their subsoil liming trials. Nitrogen fixation is greatly reduced below pH 6 and does not function at all at lower pH values. The increased yields Lathwell and Peech (1965) obtained by liming 3 inches with 4000 pounds of lime per acre over liming six inches with this same amount may have been due to the 6 inch treatment not raising the pH sufficiently for

nitrogen fixation to occur. Others, such as Longnecker and Merkle (1952) and Hourigan, Franklin, McLean and Bhumbla (1961), who have worked with subsoil liming trials, have used greenhouse experiments where surface moisture applications may have been very frequent. A number of experiments have been carried on in southeastern USA which have indicated little or no response of crop growth to applications of lime in the subsoil (Barber, 1967). The rainfall levels are higher in southeastern USA than in Alberta and this may have resulted in less moisture stress than occurred with the field experiment reported here. Another reason for lack of response of subsoil liming trials is that a negative effect may be obtained from digging. In this field experiment at all sites the plots that were dug to a depth of 50 cm, but only limed to 12.5 cm always had lower yields than the plots that were dug and limed to a depth of 12.5 cm.

All those who helped the author in preparing the plots for subsoil liming would agree that subsoil liming is not a feasible means of overcoming subsoil acidity. The large amounts of lime that would be needed to lime a soil to a depth of 50 cm or more would also make this uneconomic. Growth of species of crops tolerant to soil acidity would be the most practical method of utilizing soils with high levels of aluminum in the subsoil. Plow layer applications of lime and use of phosphorus fertilizers may increase growth on these soils particularly if the subsoil acidity is not too severe. Further work is needed in cataloguing crop varieties to determine which ones are most tolerant to high levels of aluminum and so would be suited to growth on these soils. Most areas with severe subsoil acidity problems should not have been cleared for agriculture.

Greenhouse Experiment on Subsoil Acidity

This experiment was designed to provide information on growth of alfalfa on acid soils and to determine the amount of penetration by alfalfa roots into acid subsoils. The experiment consisted of boxes with 12 cm of topsoil placed on top of 13 cm of subsoil. The ten acid soils used in this experiment each had three replicates of the following treatments:

(1) unlimed topsoil and unlimed subsoil (nil/nil);

(2) limed topsoil and unlimed subsoil (lime/nil); and

(3) limed topsoil and limed subsoil (lime/lime).

The results of this experiment (Table 8) showed that liming the topsoil and subsoil resulted in only slight increases in top growth as compared to limed topsoil and unlimed subsoil. However, liming the subsoil resulted in a considerable increase in root penetration into the subsoil. This suggests that under the conditions in the greenhouse the plants were able to get adequate water and nutrients from the topsoil. Roots in the subsoil tended to follow the surface of the polyethylene bag used to line the box, perhaps because of better aeration. To prevent such a pattern of rooting it was decided not to use polyethylene bags in further experiments.

Plate 3 shows on the nil/nil treatment the dwarfed growth and the purplish color that is typical of plants suffering from severe aluminum toxicity. The center plant in Plate 4 shows the failure of the root tip to develop when toxic levels of aluminum are present in the soil. This is in agreement with Clarkson (1968) who states one of the effects of aluminum toxicity is to kill meristematic tissue and promote branching of roots. In the soils with a high level of aluminum in the subsoil a tap

Table 8. Dry Matter Yields of Alfalfa Tops and Roots from the Greenhouse Subsoil Acidity Experiment.

Soil	Treatment	Top growth	Root yields in g/box: inside soil block 0-12cm	inside soil block 12-25cm	outside soil block* 12-25cm	Total roots
"Lowater"	nil/nil	16.6	8.0	3.8	3.3	15.4
	lime/nil	18.4	7.9	4.0	3.2	15.6
	lime/lime	18.4	7.7	6.2	3.0	17.2
"Grandin"	nil/nil	13.7	7.9	1.1	2.8	12.5
	lime/nil	16.1	10.5	0.9	5.2	17.1
	lime/lime	17.3	10.4	4.7	2.2	17.5
"Donnelly" 1	nil/nil	17.0	7.5	2.9	2.2	12.9
	lime/nil	19.2	7.8	3.2	2.1	13.4
	lime/lime	18.1	8.3	4.2	2.5	15.3
"Josephine"	nil/nil	0.01	0.03	0.0	0.0	0.03
	lime/nil	15.7	13.9	0.1	0.3	14.5
	lime/lime	15.9	10.8	5.6	1.3	17.9
"Macola"	nil/nil	25.1	14.4	8.1	1.8	24.5
	lime/nil	25.0	13.2	9.0	2.7	25.0
	lime/lime	28.3	15.0	9.0	2.0	26.1
"Athabasca"	nil/nil	22.2	13.3	7.6	2.6	24.4
	lime/nil	24.4	12.7	6.8	2.8	22.9
	lime/lime	25.2	13.0	7.1	2.9	23.4
"Donnelly" 2	nil/nil	23.8	9.5	4.7	2.5	16.7
	lime/nil	24.8	10.1	4.5	2.1	16.8
	lime/lime	23.4	10.7	5.1	2.2	18.0
"Breton"	nil/nil	19.1	9.6	4.8	3.0	17.6
	lime/nil	17.6	10.1	4.8	2.7	17.9
	lime/lime	19.4	9.2	5.5	2.6	17.6
"Donnelly" 3	nil/nil	17.4	8.1	1.9	2.3	12.3
	lime/nil	9.3	10.0	2.6	2.0	14.6
	lime/lime	22.8	10.9	3.8	2.2	17.0
"Valleyview"	nil/nil	16.7	5.1	1.7	0.3	7.1
	lime/nil	15.9	4.6	1.5	0.3	6.4
	lime/lime	16.7	5.3	1.9	0.4	7.6

* Roots that grew between the subsoil block and the plastic bag which lined the growth box.

Plate 3. Growth boxes used in the greenhouse experiment on subsoil acidity. Alfalfa grown on the Josephine soil for five weeks. On the left is the nil/nil treatment and on the right is the lime/lime treatment.

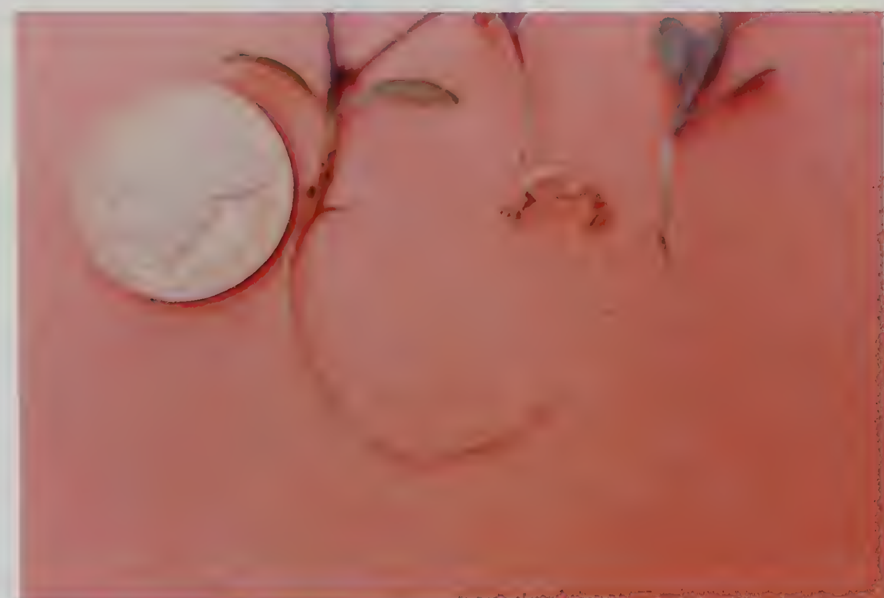


Plate 4. Roots obtained from alfalfa grown for five weeks. They are from left to right from the lime/lime, the nil/nil, and the lime/nil treatments of the Josephine soil.

Plate 5. Growth boxes at time of harvest. Wembley is "Donnelly" 2 in the text.

Plate 6.

Roots from the lime/nil treatment of the Josephine soil. This shows the development of fine roots at the 3-6 cm depths resulting from a banded phosphorus layer and also a proliferation of roots at the top of the unlimed subsoil.

root failed to develop in the unlimed subsoil (Plate 6).

Chemical analytical data on the ten soils are shown in Table 9. A number of determinations of pH, aluminum, and manganese were made on the soils before and after the experiment to establish the reproducibility of these procedures under various conditions. Some increase of pH was found in many of the moist samples when compared to the same samples when dried. Also the original topsoils from samples taken before the experiment tended to have a lower pH than the final dry topsoils after the experiment. Aluminum values varied somewhat during the experiment but not enough to appreciably alter the correlation coefficients obtained from aluminum extractions at different times. Manganese levels in the original subsoils were not high enough to be toxic to plant growth according to Penney (1973). These manganese values declined during the experiment (Table 9).

Root growth ratios and top growth ratios were correlated with various analytical data from the unlimed soils (Table 10). These correlations indicate:

(1) The yields of alfalfa top growth and alfalfa roots in the 12-25 cm depths on the nil/nil treatments as contrasted to the lime/lime treatments were significantly correlated to pH of the topsoil, pH of the subsoil, to aluminum levels in the topsoil, and aluminum levels in the subsoil. This means that response of alfalfa to lime as measured by top growth and subsoil root yields is significantly correlated to the soil pH and also significantly correlated with subsoil and topsoil aluminum levels.

(2) The top growth and the root yields in the 0-25 cm depths when the topsoil was limed and the subsoil was not limed (lime/nil), when contrasted

Table 9. Soil pH, $CaCl_2$ Soluble and KCl Extractable Aluminum and Manganese for Soils from Greenhouse Subsoil Acidity Experiment.

		pH of			Soluble Al (ppm) of			Exchangeable Al (ppm) of		Soluble Mn (ppm) of	
Soil	Depth	orig. dry soil	moist soil	final dry soil	orig. dry soil	moist soil	final dry soil	orig. dry soil	moist soil	orig. dry soil	moist soil
"Lowater"	0-12 cm	5.2	5.7	5.5	1.0	1.2	2.1	31	64	14.1	3.3
	12-25cm	5.2	5.0	5.1	6.5	3.5	4.7	156	138	5.4	4.8
"Grandin"	0-12cm	5.1	5.6	5.4	2.0	1.2	-	24	30	18.6	4.1
	12-25cm	4.8	4.5	4.5	15.8	12.6	22.9	289	340	2.6	3.9
"Donnelly" 1	0-12cm	5.4	5.7	5.5	1.2	1.3	1.3	45	33	5.4	1.9
	12-25cm	5.4	5.6	5.4	0.9	1.0	1.2	44	37	1.1	1.3
"Josephine"	0-12cm	4.5	4.4	4.4	55.5	65.8	59.2	535	717	0.3	3.4
	12-25cm	4.3	4.2	4.2	82.0	71.7	77.2	894	797	0.7	1.0
"Macola"	0-12cm	5.4	5.8	5.7	0.8	0.6	1.1	10	9	8.7	1.5
	12-25cm	4.9	5.2	5.1	3.8	4.0	3.5	142	142	0.4	2.4
"Athabasca"	0-12cm	6.0	6.6	6.2	0.5	0.1	0.6	0	0	9.0	0.9
	12-25cm	5.9	6.0	6.0	0.3	0.3	0.2	4	1	0.1	0.4
"Donnelly" 2	0-12cm	6.0	6.6	6.2	0.2	0.3	0.3	1	0	0.2	0.9
	12-25cm	5.3	5.7	5.4	3.9	3.2	3.5	166	135	1.0	1.4
"Breton"	0-12cm	5.6	6.2	6.0	0.4	0.5	1.3	5	11	17.8	1.6
	12-25cm	5.4	5.6	5.7	0.9	0.8	1.1	5	14	2.4	1.7
"Donnelly" 3	0-12cm	5.3	5.7	5.5	1.6	1.5	2.8	27	33	7.8	2.4
	12-25cm	5.1	5.3	5.0	4.7	5.3	6.8	178	116	3.3	3.1
"Valleyview"	0-12cm	5.4	5.4	5.2	1.4	2.3	2.7	74	112	4.5	2.7
	12-25cm	5.9	6.0	6.0	0.6	0.7	0.7	27	14	0.2	0.2

Table 10. Correlation Coefficients of Root Growth Ratios and Top Growth Ratios with Analytical Data from the Greenhouse Experiment on Subsoil Acidity.

Ratios of yields on different treatments	Correlation Coefficients											
	pH of top-soil	pH of subsoil			$CaCl_2$ soluble Al in topsoil	$CaCl_2$ soluble Al in subsoil			KCl exchangeable Al in subsoil		$CaCl_2$ soluble Mn in subsoil	
	⊕orig.	⊕orig.	ϴmoist	∅dry	orig.	orig.	moist	dry	orig.	moist	orig.	moist
Alfalfa top growth												
nil/nil: lime/lime	0.79*	0.75	0.76	0.63	-0.97	-0.97	-0.98	-0.97	-0.95	-0.94	0.10	0.07
lime/nil: lime/lime	0.15	0.13	0.11	0.20	0.13	0.11	0.09	0.07	0.10	0.07	-0.14	-0.25
Total roots, 12-25 cm												
nil/nil: lime/lime	0.87	0.74	0.82	0.66	-0.92	-0.95	-0.95	-0.97	-0.93	-0.95	0.04	-0.01
lime/nil: lime/lime	0.76	0.56	0.60	0.49	-0.95	-0.93	-0.93	-0.91	-0.88	-0.85	0.09	0.20

⊕ original soil prior to the start of the experiment.
ϴ fresh moist soil from the boxes after the experiment.
∅ dried soil from the boxes after the experiment.
* Those r values greater than ± 0.602 are significant at the 5% level of probability and the r values above ±0.735 are significant at the 1% level of probability.

to the lime/lime treatments showed no relationship to any of the chemical analytical data. This suggests that under these conditions in the greenhouse increased root yields obtained by liming the subsoil do not directly correlate with the subsoil pH or the presence of aluminum or manganese in the subsoil.

(3) The root yields in the 12-25 cm depths on the lime/nil treatments as contrasted to the lime/lime treatments show a significant relationship with aluminum levels of the subsoil and some relationship to pH of the subsoil. This means the response of alfalfa to subsoil liming as measured by increased subsoil root yield is significantly correlated with subsoil aluminum levels.

(4) No relationship of any of the growth ratios was found with the manganese level in the subsoil.

(5) Soluble and exchangeable aluminum values are more sensitive than pH values as an indicator of alfalfa top growth response to liming and as an indicator of alfalfa root growth in an unlimed soil.

Growth Cabinet Experiment with Phosphorus

Results of the growth cabinet experiment with phosphorus (Table 11) show that a large application of phosphorus is more effective than lime in improving growth on an acid soil which is already fertilized with low levels of phosphorus. Rios and Pearson (1964) show that phosphorus is mobile within a plant and surface applications of phosphorus supply phosphorus needs for root penetration into the subsoil. Results (Table 11) indicate that some increase in root penetration occurred in the subsoil of the P/nil (phosphorus in topsoil and untreated subsoil) treatment as com-

Table 11. Top and Root Yields of Barley Grown on an Acid Soil from Growth Cabinet Experiment with Phosphorus.

Treatment	Top yields g/pot	Topsoil root yields g/pot	Subsoil root yields g/pot
nil/nil	4.57c⊕	1.66b	0.360c
lime/lime	5.52bc	1.50b	0.393bc
phosphorus/nil	6.65ab	2.22a	0.435b
phosphorus/phosphorus	7.10a	2.12a	0.665a
F	5.1*	13.6**	9.6**
LSD	1.24	0.29	0.074

⊕ In each column those values which are not followed by the same letter are significantly different at an LSD value at a 100:1 error seriousness ratio according to the method of Waller and Duncan (1969).

* F value is significant at the 5% level of probability.

** F value is significant at the 1% level of probability.

Table 12. Chemical Analyses of Soils Used in the Growth Cabinet Experiment with Phosphorus.

Treatment	Depth	pH	Al (ppm)
nil	topsoil	5.4	3.7
nil	subsoil	5.0	4.1
lime	topsoil	6.8	0.2
lime	subsoil	6.5	0.2
phosphorus	topsoil	5.7	5.8
nil	subsoil	5.2	6.8
phosphorus	topsoil	5.8	5.7
phosphorus	subsoil	5.2	6.2

pared to the root penetration into the subsoil on the nil/nil treatment. The application of phosphorus (at 150 ppm as KH_2PO_4) to the subsoil greatly increased root growth in the subsoil. These results indicate that the mobility of phosphorus within a plant means that surface applications of phosphorus serve as a partial means of overcoming subsoil acidity. Further experiments with more acid soils and different levels of phosphorus would be needed to establish how complete this is.

Soil aluminum levels were increased in the soils treated with high levels of phosphorus, yet pH values were also increased (Table 12). It appears that this increase in aluminum is due to the salt effect of the KH_2PO_4 which was used to supply phosphorus. This increase in pH and increase in aluminum is referred to by Coleman and Thomas (1967). They state that salts can exchange aluminum, hydrogen, and hydroxyl ions. Ordinarily the amount of aluminum ions exchanged exceeds the amount of hydroxyl ions exchanged and the pH falls, but if the reverse is true, the pH rises. In this experiment the effect of the added KH_2PO_4 was to increase concentration of both hydroxyl and aluminum ions. The formation of insoluble aluminum phosphates did not occur to sufficient extent to lower the soluble aluminum levels in the soil in this experiment. Increased plant growth under increased levels of aluminum indicates that the effect of the phosphorus was to alleviate the aluminum toxicity at the root surface or within the plant.

The results of this experiment indicate that phosphorus fertilizer applications to acid soils at rates slightly heavier than normal should be considered as part of a liming and fertilization program. The high cost of phosphorus fertilizers makes the cost of large applications of phosphorus prohibitive. Soils with acid subsoils should respond well to rates

of phosphorus several times larger than would normally be applied. Field tests should be carried out to establish what are suitable rates of phosphorus and lime to use on acid soils.

Greenhouse Experiment with Temperature and Acidity of Subsoils

An experiment was set up to determine if any interaction existed between the temperature of the subsoil and aluminum toxicity as expressed by penetration of roots into the subsoil or by top growth. Ladak alfalfa was grown on three soils. Each soil was limed to obtain three levels of aluminum in the subsoil. Three subsoil temperatures were used with two replicates of each treatment.

The results (Table 13) indicate that there were not any measurable interactions of temperature and soil aluminum level with top growth. Top growth was significantly improved by liming the subsoil. The differences in top growth at different temperature levels (Tables 13 and 14) are significant at the 5 per cent level with analysis of variance but do not give a statistically significant LSD value at the 100:1 error seriousness ratio (Waller and Duncan, 1969). There does appear to be a real difference here, but it is hard to measure by conventional statistical tests because of the limited replication in this experiment.

The yield of roots in the topsoil was significantly reduced by increasing temperatures in the subsoil (Table 15). This decrease of root yield with increasing temperature is caused by greater root penetration in the subsoil at higher temperatures and also it is caused by a lower root to top ratio which occurs with increasing temperatures.

A highly significant increase of root yields in the subsoil occurred with increases of the level of lime in the subsoil (Tables 15, 16

Table 13. Yields of Top Growth of Alfalfa for Various Levels of Lime for Greenhouse Experiment with Temperature and Acidity of Subsoils.

Subsoil lime level	Yield of top growth (g/pot) 8°C	14°C	21°C	Average
Silver Valley				
no lime	5.20	4.50	5.42	5.04
some lime	5.15	5.55	5.86	5.52
neutral	5.50	6.58	6.45	6.18
Prespatou				
no lime	4.34	4.51	4.30	4.39
some lime	4.80	5.13	5.16	5.03
neutral	5.45	5.67	6.59	5.90
Bessborough				
no lime	6.00	5.92	6.79	6.23
some lime	5.12	6.77	6.86	6.25
neutral	7.35	7.86	7.70	7.63
Average	5.43a♁	5.79a	6.12a	

Table 14. Analysis of Variance for Yields of Alfalfa Top Growth for the Greenhouse Experiment with Temperature and Acidity of Subsoils.

Analysis of Variance	F	LSD
lime levels	20.6**	1.21
soils	28.7**	1.19
temperatures	5.1*	1.32
soils x temperatures	0.37	
soils x lime	0.73	
temperatures x lime	0.99	
soils x temperatures x lime	0.82	

♁ All those values which are not followed by the same letter are significantly different at an LSD value at a 100:1 error seriousness ratio according to the method of Waller and Duncan (1969).

* F value is significant at the 5% level of probability.

** F value is significant at the 1% level of probability.

Table 15. Root Yields of Alfalfa for Greenhouse Experiment with Temperature and Acidity of Subsoils.

Subsoil lime level	Root yields in topsoil (g/pot) 8°C	14°C	21°C	Ave.	Root yields in subsoil (g/pot) 8°C	14°C	21°C	Ave.	Total ave. root yield
Silver Valley									
no lime	3.71	2.97	1.97	2.89	0.15	0.23	0.20	0.19c	3.08
some lime	3.69	3.19	2.78	3.24	0.42	0.49	0.52	0.47bc	3.71
neutral	3.39	2.91	2.36	2.85	0.99	1.39	0.95	1.11a	3.96
Prespatou									
no lime	3.22	2.62	1.99	2.61	0.43	0.54	0.56	0.51bc	3.12
some lime	3.17	2.27	1.87	2.44	0.43	0.67	0.56	0.55bc	2.99
neutral	2.98	2.73	2.03	2.58	0.70	1.22	1.26	1.06a	3.64
Bessborough									
no lime	3.21	2.78	1.97	2.66	0.47	0.56	0.60	0.54bc	3.20
some lime	2.75	2.44	2.36	2.66	0.48	0.64	0.65	0.59bc	3.25
neutral	3.63	3.10	2.25	3.03	0.54	0.89	0.79	0.74ab	3.77
Average	3.31a	2.78ab	2.18b		0.51a	0.74a	0.68a♁		

Table 16. Analysis of Variance for Root Yields of Alfalfa for the Greenhouse Experiment with Temperature and Acidity of Subsoils.

Analysis of variance	Topsoil root yields F	LSD	Subsoil root yields F	LSD
lime levels	0.20		39.3**	0.35
soils	7.65**	0.69	1.64	
temperatures	50.3**	0.64	6.29**	0.39
soils x temperatures	0.09		0.61	
soils x lime	1.47		5.45**	0.41
lime x temperatures	1.11		1.19	
soils x lime x temperatures	0.61		0.46	

♁ All those values which are not followed by the same letter are significantly different at an LSD value at a 100:1 error seriousness ratio according to the method of Waller and Duncan (1969).

** F value is significant at the 1% level of probability.

Table 17. Subsoil Lime Level, Alfalfa Top Growth and Subsoil Root Yield.

	Yield (g/pot)		
	No lime	Some lime	Neutral
Top growth	5.22b[⊕]	5.59ab	6.63a
Subsoil root yield	0.41b	0.54b	0.97a

⊕ In each row those values which are not followed by the same letter are significantly different at an LSD value at a 100:1 error seriousness ratio according to the method of Waller and Duncan (1969).

---

and 17). The interaction of lime levels and soils with root yields in the subsoil was significant. This interaction could be expected to be significant because the different soils contained various levels of aluminum in the subsoil and should show different degrees of response to lime. The largest root yields in the subsoil occurred in the pots grown at 14°C. The subsoil root yields did not interact with temperature and lime or temperatures and soils or with temperatures, lime and soils. This is in contrast with the findings of Cheng, Bourget and Ouellette who suggest (1971) that aluminum toxicity is more important at low temperatures than at high temperatures. The limited replication in the present experiment reduced the sensitivity of the measurement of this interaction. Nevertheless, any increase in aluminum toxicity at lower temperatures appears not to be a major factor controlling plant growth or plant root development.

Different levels of soluble aluminum in the subsoil could not be detected in the pots kept at different temperatures (Table 18). It was not possible to analyze the fresh soil samples for aluminum immediately.

Table 18. Soil pH and 0.02M $CaCl_2$-Soluble Aluminum Levels in the Subsoils After Harvest from the Greenhouse Experiment with Temperature and Acidity of Subsoils.

Subsoil lime level	Temperature 8°C pH	Al(ppm)	14°C pH	Al(ppm)	21°C pH	Al(ppm)
Silver Valley						
no lime	4.07	84.0	4.07	78.0	4.02	83.0
some lime	4.44	49.3	4.34	47.9	4.28	48.8
neutral	5.60	0.5	5.95	0.8	5.60	0.0
Prespatou						
no lime	4.60	21.9	4.58	24.7	4.48	25.0
some lime	4.77	11.1	4.83	13.3	4.68	13.1
neutral	5.78	0.0	5.79	0.1	5.76	0.0
Bessborough						
no lime	4.90	14.5	4.80	16.0	4.70	14.3
some lime	4.91	11.6	4.81	12.8	4.76	12.1
neutral	6.17	0.1	6.22	0.2	6.03	0.5

The soil samples were air dried and stored for about three months and then analyzed for aluminum. The numerous aluminum analyses done on fresh and dried samples in the greenhouse experiment on subsoil acidity, indicated, however, that there were not any major differences in results between fresh and dry samples. The subsoils showed a very slight decline in pH with increasing temperatures.

Psychrometers provided a useful means of monitoring water levels in the subsoil. It was found with large, rapidly growing plants it was necessary to keep the pots above field capacity for about two days to get water down into the subsoils. This at times meant some reduction in water use rates because of waterlogged conditions existing around the roots. Water use measurements were made by weighing the pots and water use is given in Table 19. Significant F values were obtained (Table 20)

Plate 7. Wet style soft drink coolers were used as temperature regulating baths for the greenhouse experiment with temperature and acidity of subsoils.

Plate 8.

Cans used as soil containers for the greenhouse experiment with temperature and acidity of subsoils. "Loep" soil is referred to in the text as "Prespatou". The cylinder on the left is equipped with psychrometers and thermocouples.

Table 19. Water Use of Alfalfa for Three Dates for Various Levels of Lime for Greenhouse Experiment with Temperature and Acidity of Subsoils.

	Water used (ml/pot)									
	8°C			14°C			21°C			
Subsoil lime level	Feb.28	Mar.9	Mar.17	Feb.28	Mar.9	Mar.17	Feb.28	Mar.9	Mar.17	Average
Silver Valley										
no lime	232	257	329	246	284	331	252	280	337	283
some lime	242	266	347	277	306	361	278	305	387	308
neutral	291	319	406	335	355	416	335	373	441	364
Prespatou										
no lime	339	370	446	386	436	482	353	420	482	413
some lime	390	460	470	391	460	520	343	427	532	444
neutral	420	459	505	518	545	567	438	524	548	503
Bessborough										
no lime	481	552	557	531	591	595	579	645	591	569
some lime	408	527	541	541	578	597	584	655	608	560
neutral	540	591	584	608	648	623	639	663	648	616

Table 20. Analysis of Variance for Water Use of Alfalfa for Greenhouse Experiment on Temperature and Acidity of Subsoils.

Analysis of variance	F	LSD
lime levels	12.6**	45
soils	150 **	41
temperatures	6.4**	53
dates of watering	15.4**	44
soils x temperatures	1.3	
soils x dates	1.46	
soils x temperatures x lime levels	0.25	

Table 21. Water Use of Alfalfa Plants as Related to Subsoil Lime Level.

Average Water Consumption (ml/pot)		
No lime	Lime added	Neutral
423b⊕	437b	494a

Table 22. Water Use of Alfalfa as Related to Subsoil Temperature.

Average Water Consumption (ml/pot)		
8°C	14°C	21°C
420a⊕	464a	469a

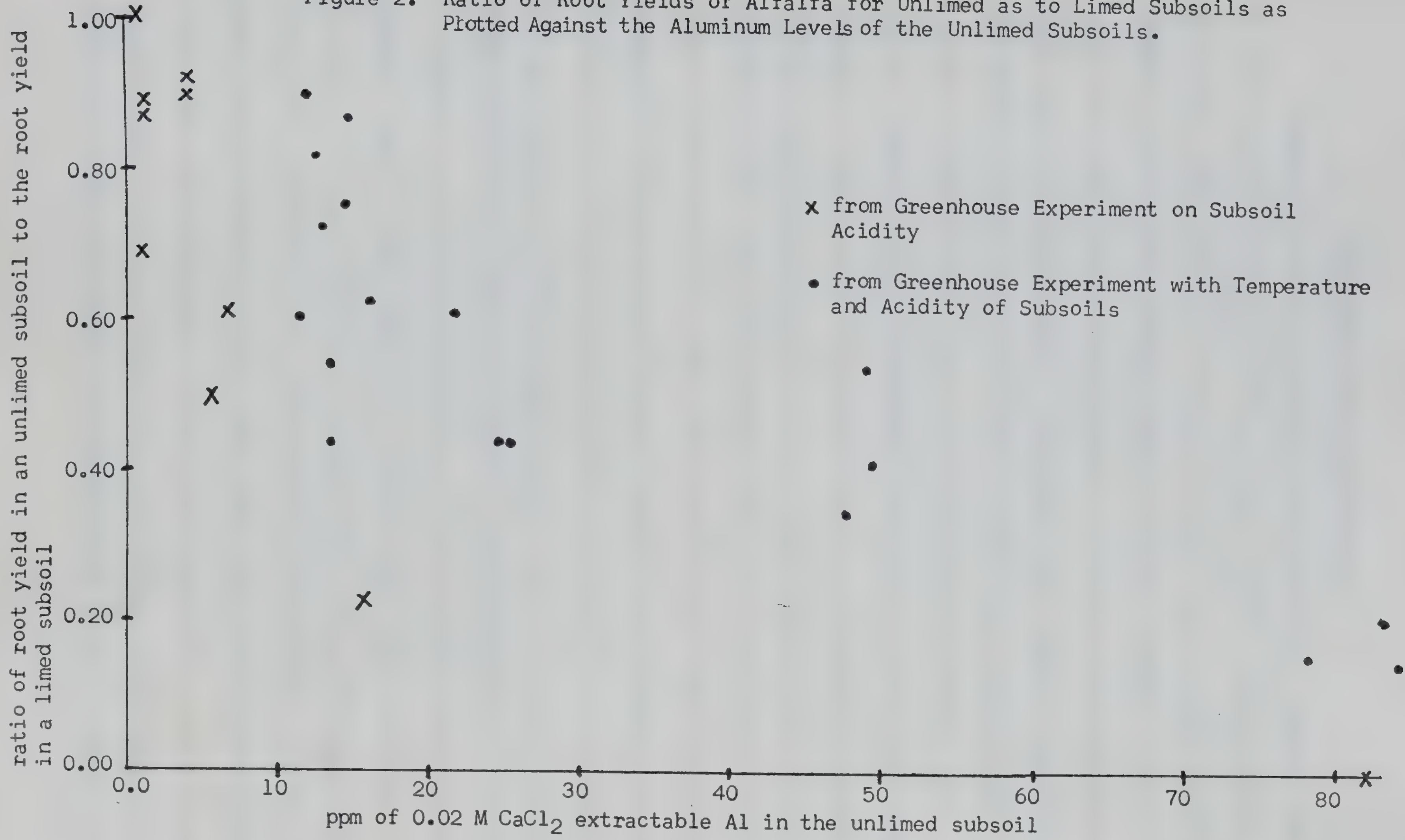
** F value is significant at the 1% level of probability.
⊕ In each table those values which are not followed by the same letter are significantly different at an LSD value at a 100:1 error seriousness ratio according to the method of Waller and Duncan (1969).

on alfalfa water use for different soils, subsoil lime levels, subsoil temperatures, and dates of weighing. However, interactions of the first, second and third level in all cases were not significant. The increase in consumption of water recorded on the pots with limed subsoils (Table 21) was significant. This indicates that after the subsoil is limed

the alfalfa roots are more effective in absorbing water from the subsoil. One of the effects of toxic levels of aluminum on plant roots is the reduction of water uptake (Lance and Pearson, 1969). Water consumption for three temperatures is shown in Table 22. In this experiment water consumption did not show any measurably significant interaction between soils, temperatures and lime levels. This means that plants grown under greenhouse temperatures should provide fairly accurate predictions of the toxic level of aluminum under field conditions at lower temperatures. This also is in agreement with the findings that neither top growth nor root yields in the subsoil showed any interactions with soils and temperatures or with lime levels and temperatures. The results here indicate that the use of water is a sensitive means of measuring root function and penetration in an acid soil.

A chart (Figure 2) was prepared to show the relationship between increased alfalfa root growth obtained by liming the subsoil and the level of soluble aluminum present in the subsoil. Data from the greenhouse experiment on subsoil acidity and the greenhouse experiment with temperature and acidity of subsoils were used. The increased root yields in the subsoil in response to liming were evident at very low levels of aluminum (3 ppm or less) in the subsoil. At levels of aluminum of 20 ppm or more most of the roots occurred in the first few cm of the unlimed subsoil and the root yield in the unlimed soil was approximately half of the root yield in the limed subsoil. The response to liming is in direct proportion to the aluminum level in the subsoil. This is in agreement with Rios and Pearson (1964) who report that lower root yields of cotton and sudangrass were found in acid subsoils than were found in limed subsoils.

Figure 2. Ratio of Root Yields of Alfalfa for Unlimed as to Limed Subsoils as Plotted Against the Aluminum Levels of the Unlimed Subsoils.



Nutrient Culture Experiment

A number of barley varieties were screened for aluminum tolerance by a method developed by Foy and Brown (1964). Two preliminary trials were made, the first of these had to be cut short due to a serious infection by water molds in the nutrient culture solution. Later another trial had to be abandoned because of an invasion by mice which consumed many of the barley seeds. The first trial indicated that with high levels of aluminum Olli and Volla barley showed better growth than did Galt and Husky barley. The second trial included Pendek oats as well as a number of barley varieties. Pendek oats showed a much greater tolerance to toxic levels of aluminum than any of the barley varieties. The third trial indicated the varieties Betzes and Olli were the most tolerant to toxic levels of aluminum (Table 23). Root growth and top growth of Betzes and Olli barley were significantly longer than the other varieties at 12 ppm aluminum (Plate 9), and at 4 ppm aluminum top growth of Betzes and Olli barley were significantly longer than top growth of the other varieties. The varieties Conquest and Galt showed the least resistance to toxic levels of aluminum. The retardation of root growth by aluminum was large even in the case of the varieties most tolerant to aluminum, such as Olli (Plate 10). Penney (1973) found that Betzes barley was significantly better than Husky, Olli, Galt, and Bonanza when grown in the greenhouse on a soil with 8.5 ppm 0.02M $CaCl_2$-soluble aluminum. In field trials on acid soils using Olli and Galt barley, Penney (1973) obtained significantly larger yield increases on liming from Galt than from Olli. Olli is an early maturing variety which might have use on acid soils high in soluble aluminum for late seeding. Betzes has a

Table 23. Top and Root Lengths of Barley Varieties Grown in Nutrient Solution with Various Levels of Aluminum.

	Lengths of tops and roots (in cm)					
	0 ppm aluminum		4 ppm aluminum		12 ppm aluminum	
Varieties	top	root	top	root	top	root
Conquest	21.4d♁	23.4ab	18.3cd	3.1cd	13.9c	2.4c
Bonanza	23.4abcd	23.8a	19.6bc	3.4bcd	16.3b	2.9b
Olli	26.3a	20.8abc	24.0a	5.2a	20.5a	3.6ab
Centennial	22.8bcd	22.5ab	20.8b	3.6bcd	16.8b	2.5c
Betzes	25.1abc	21.4abc	23.6a	4.5abc	20.6a	4.3a
Volla	25.3ab	21.9abc	20.1b	4.4abc	16.1b	3.2bc
Galt	22.3bcd	19.6bc	17.6d	2.4d	13.7c	2.6c
Jubilee	21.9cd	19.4c	20.7b	4.8ab	16.3b	2.7c
Mean	23.6	21.6	20.6	3.9	16.7	3.0
F	3.1*	2.4	13.7**	4.33**	16.4**	5.70**
LSD	3.33	3.91	1.69	1.40	1.76	0.81

♁ In each column those values which are not followed by the same letter are significantly different at an LSD value at a 100:1 error seriousness ratio according to the method of Waller and Duncan (1969).

* F value is significant at the 5% level of probability.

** F value is significant at the 1% level of probability.

high yield potential and seems to offer the most promise for use on acid soils high in aluminum.

Good seed quality must be maintained as the short growth time of 14 days means the plant is greatly influenced by seedling vigor. Volla

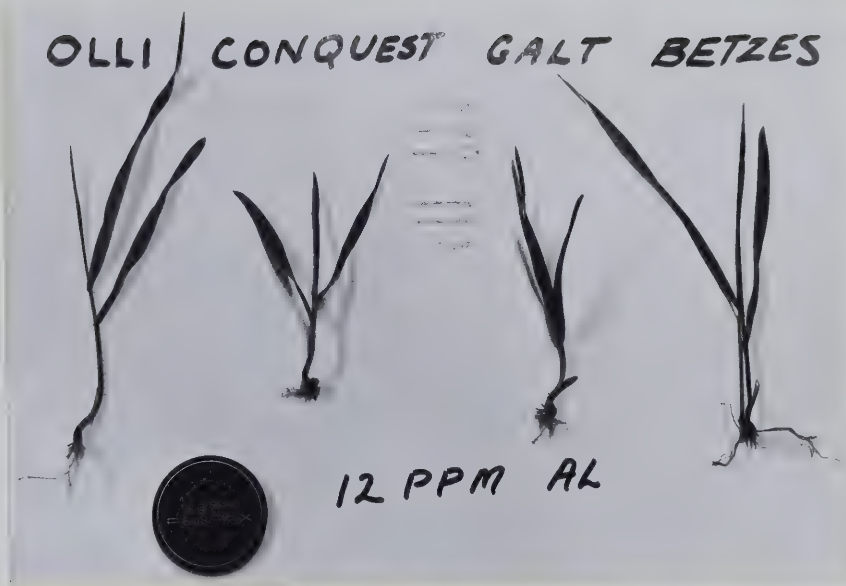


Plate 9. Four barley varieties grown in nutrient solutions containing 12 ppm aluminum. All show severe stunting of roots due to aluminum toxicity.

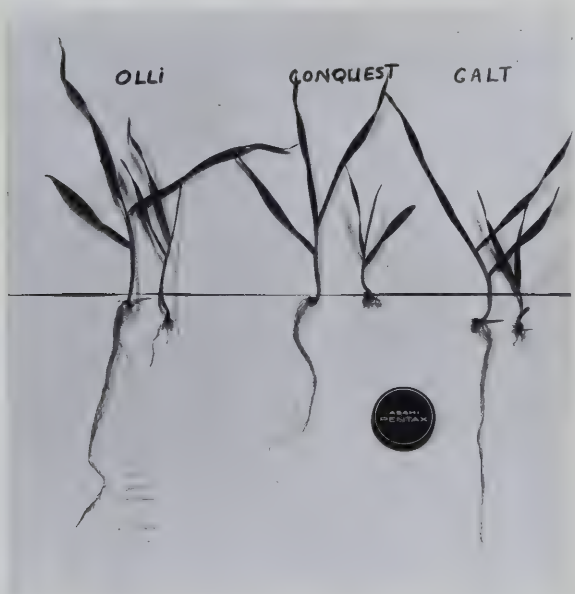


Plate 10. Three barley varieties are shown with a plant grown at 0 ppm aluminum at the left and a plant grown at 12 ppm aluminum at the right.

barley did well in an early trial and not so well in the third trial. This difference may be due to the seed having been stored in a warm dry lab resulting in a decline in vigor.

The nutrient culture method seems to offer good possibilities for testing crop variety reaction to chemical factors in the soil environment. The results of this experiment are in general in agreement with Penney's reports (1973) of aluminum tolerance of barley varieties grown in acid soils. A test for aluminum tolerance does not imply manganese tolerance. Other tests would need to be done to determine manganese tolerance of barley varieties. The varieties tested in this experiment did not show the range in tolerances to aluminum that Reid, Fleming and Foy (1971) found in barley. This may be due to differences in method. Reid, et al grew their varieties in separate containers of nutrient solution and did not make adjustments of solution pH values. Some varieties increased the pH to their benefit, others lowered the pH to their detriment. Further screening of varieties of barley and perhaps further breeding of new varieties is necessary to find a variety which is tolerant to high levels of aluminum and suited to northern Alberta conditions.

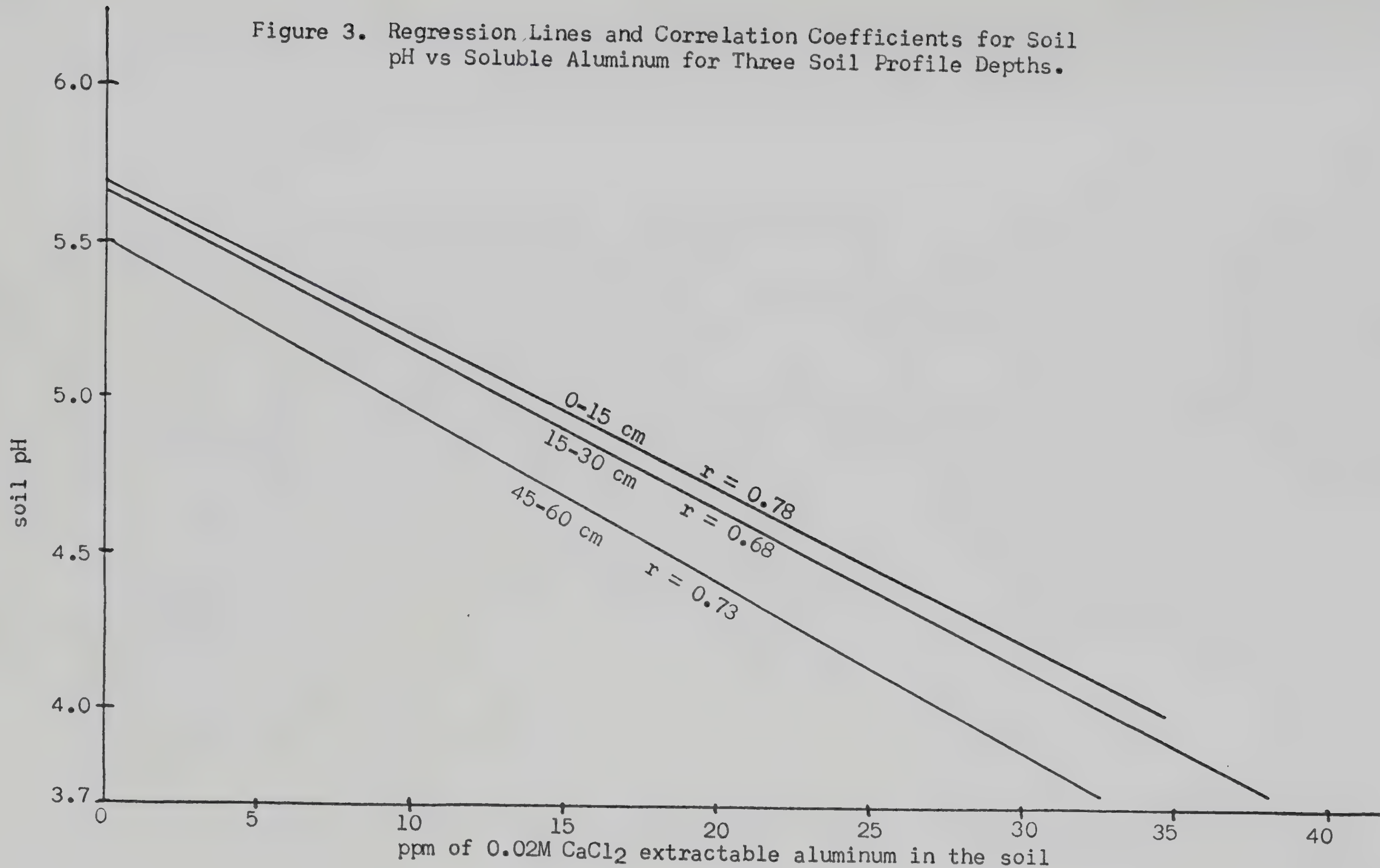
Field Survey on Subsoil Acidity

A reconnaissance type of field survey was conducted to determine the agricultural areas in Alberta and northeastern British Columbia where subsoil acidity exists at levels sufficient to cause impairment of crop growth. Most of the sites sampled were cultivated fields or virgin land adjacent to cultivated fields. It was found that a number of areas contain soils which have quite low soil pH's and toxic levels of aluminum in surface and subsurface horizons. Several profiles showed high levels of soluble manganese, but this was highest in surface horizons.

Soil pH, soluble aluminum, and soluble manganese values for profiles from the field survey and type profiles for soil series are shown in Appendix III. The lowest pH values and highest levels of soluble aluminum were usually found in the 15-30 cm layer which corresponds to the upper part of the Bt horizon. When 189 profiles from the field survey were compared, the 0-15, 15-30, and 45-60 cm layers had, respectively, 48, 82, and 55 profiles with a pH value from 5.0 to 5.7 and 14, 31, and 33 profiles with a pH value below 5.0. Levels of soluble manganese were highest in surface horizons and were seldom found at levels which might be toxic to plants in subsurface horizons. A correlation of soil pH to levels of soluble aluminum was made. The slope of the regression equation and correlation coefficient (r) values are shown in Figure 3. When pH was correlated with soluble aluminum, the r values for the various depths range from 0.68 to 0.78. These values are significant, but only about 50 or 60 per cent of the variability in aluminum content can be predicted from pH values.

Maps were prepared to show the areas which have high levels of soluble aluminum in the 0-15, 15-30, and 45-60 cm depths (Figures 4-8). The largest area which had soils with severely acid subsoils was in northeastern British Columbia extending from Charlie Lake, Murdale, and Cecil Lake, north to the Blueberry River, Prespatou, Nig Creek, and the Beaton River. The Federal Soil Survey at Vancouver provided typical soil profiles from this area and further west and north, near the Alaska highway. The typical profiles from the Alcan, Milligan, Osborn, Boundary, Buick and Jedney series had low soil pH and toxic levels of aluminum in surface and subsurface horizons. Very high levels of aluminum in the subsoils were also found in the Bessborough, B.C. area and in Alberta in the Silver Valley area, Savage Prairie area, and in the Plamondon to Lac La

Figure 3. Regression Lines and Correlation Coefficients for Soil pH vs Soluble Aluminum for Three Soil Profile Depths.



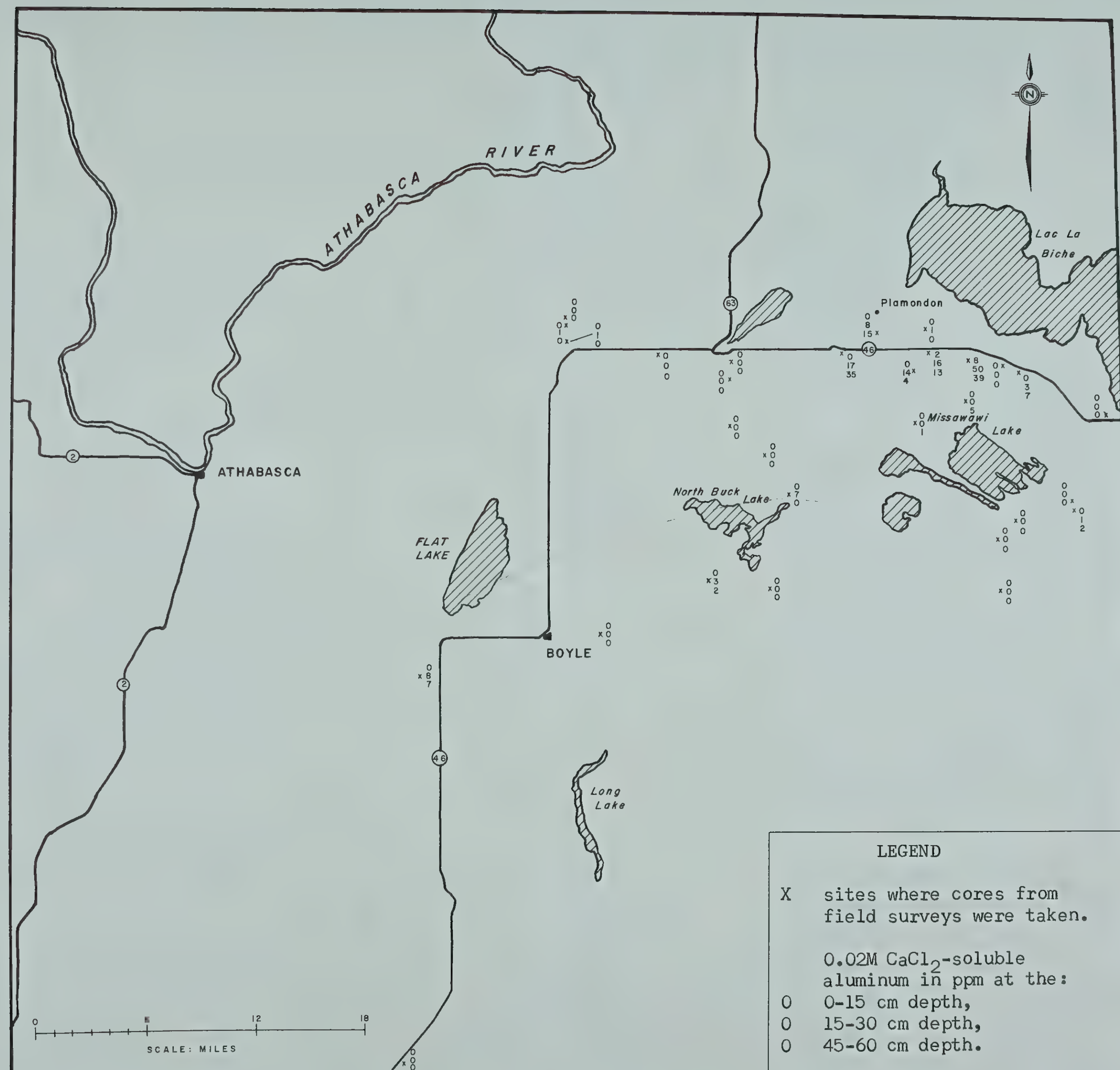
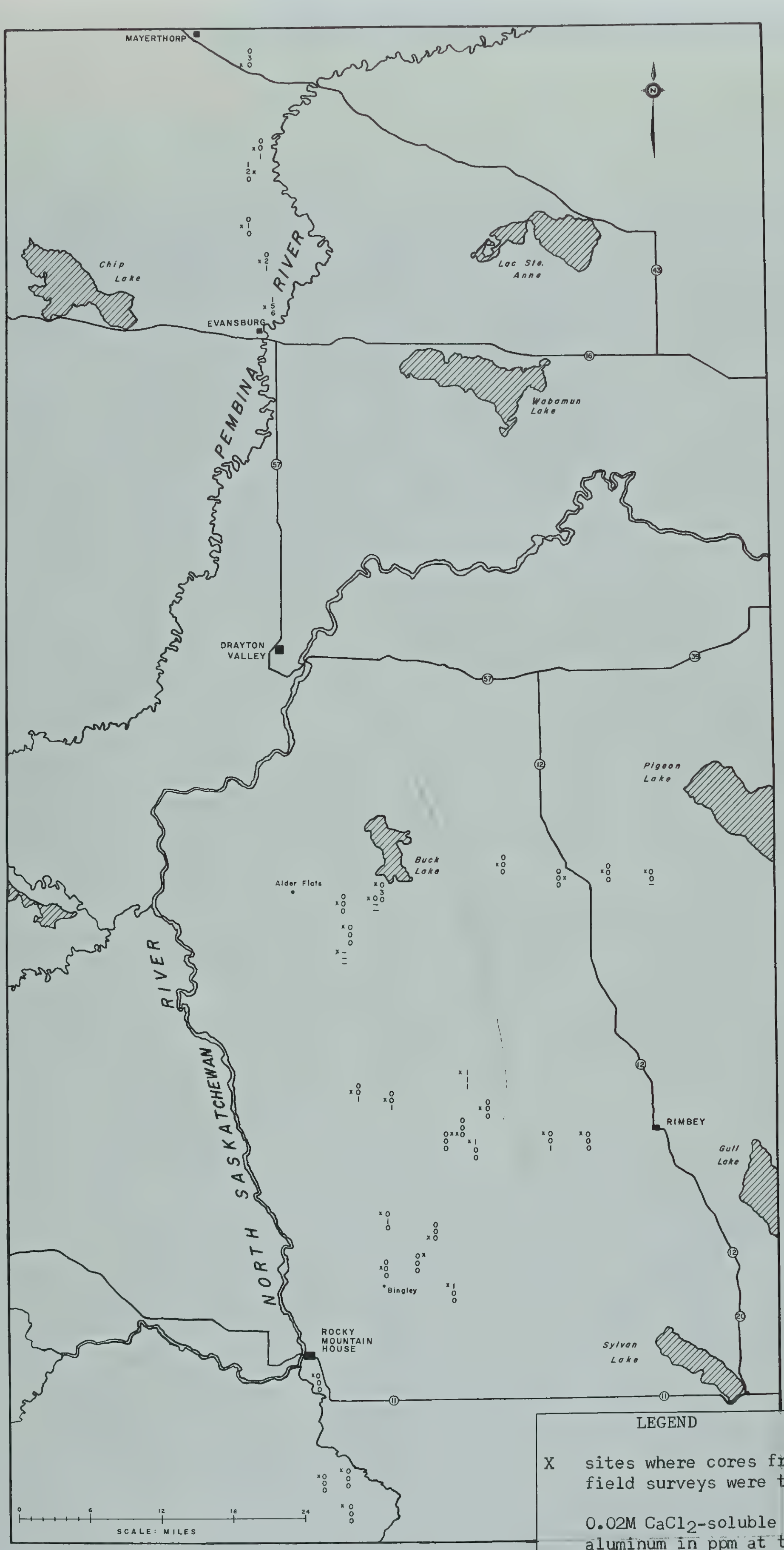


Figure 4. LAC LA BICHE AREA OF ALBERTA



LEGEND

X sites where cores from field surveys were taken.

0.02M $CaCl_2$-soluble aluminum in ppm at the:
0 0-15 cm depth,
0 15-30 cm depth,
0 45-60 cm depth.

Figure 5.

BUCK LAKE AREA
OF ALBERTA

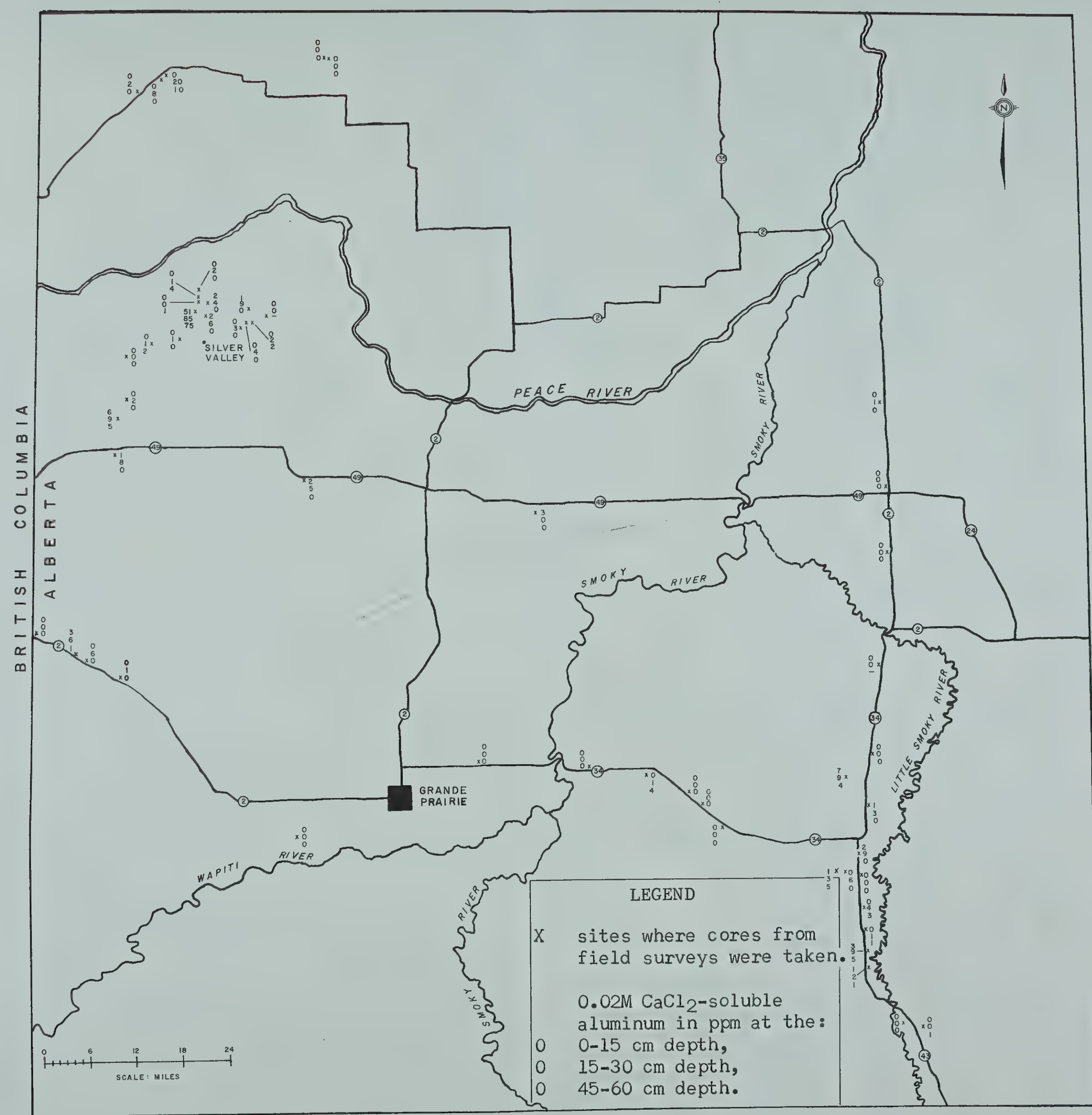


Figure 6. PEACE RIVER AREA OF ALBERTA

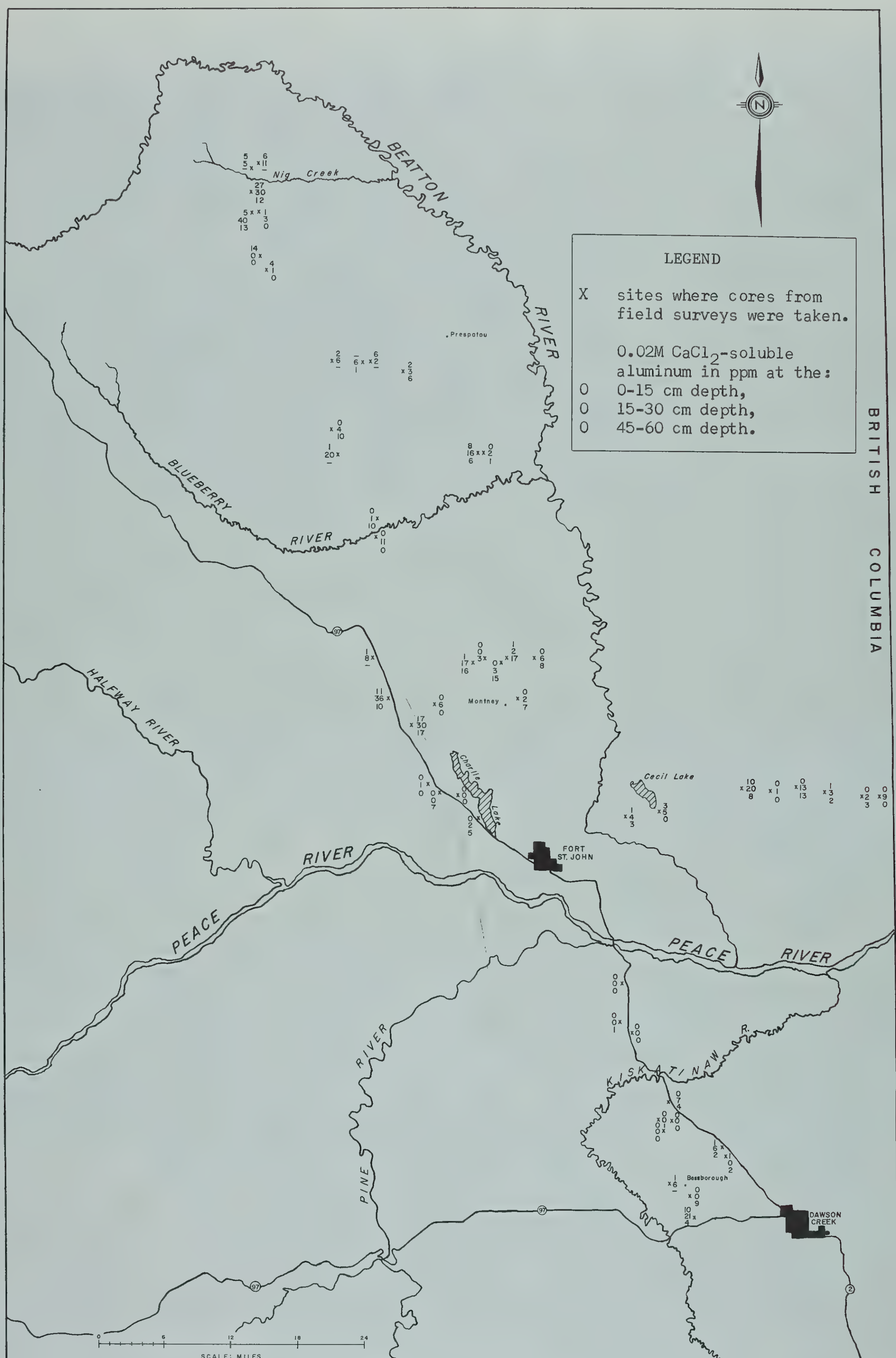


Figure 7.

PEACE RIVER AREA
OF BRITISH COLUMBIA

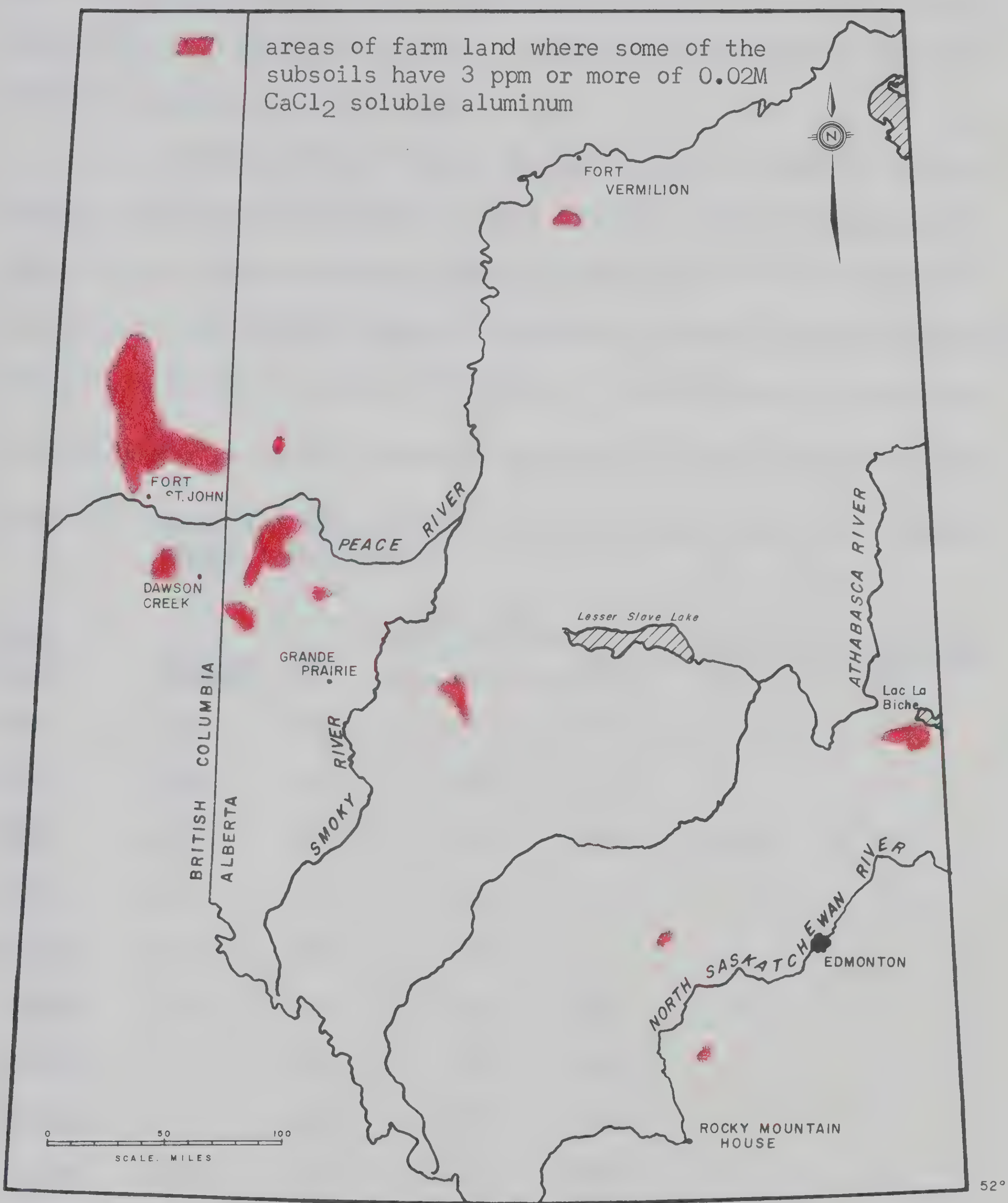


Figure 8. AREAS WHICH CONTAIN SOILS WITH TOXIC LEVELS OF ALUMINUM IN THE SUBSOIL

Biche area. The Valleyview, Evansburg, Whitecourt and Bingley to Alder Flats areas in Alberta had some acid soils with levels of soluble aluminum which were sufficiently high to reduce root penetration and top growth of aluminum-sensitive crops.

At one site (Silver Valley, NE 10-82-10-6) on a Humic Eluviated Gleysol of the Josephine series, a deep hole was dug to determine the nature of the underlying parent material and establish if a lime layer was present. The profile examined showed no lime layer and was extremely acid to a depth of 2.7 meters (Table 24). The Ap horizon was analyzed

---

Table 24. Analytical Data on Cores from a Deep Hole on a Soil from the Josephine Soil Series.

Depth in cm	Horizon	pH	ppm 0.02M $CaCl_2$ soluble Al	ppm 1M KCl exchangeable (ppm) Al	Ca	Na
0-23	Ap	4.5	54	700	825	125
23-43	Btg	4.2	87	-	-	-
43-60	Cg	3.9	72	925	1050	150
60-90	Cg	3.7	66	-	-	-
90-120	Cg	3.6	62	-	-	-
120-150	Cg	3.6	64	605	-	-
150-180	Cg	3.6	62	545	-	-
180-210	Cg	3.7	52	465	-	-
210-240	Cg*	3.9	252	770	-	-
240-270	Cg*	3.6	306	-	-	-

* Large selenite ($CaSO_4$) crystals were present.

for sulphur. Soluble and HI extractable sulphur values were 2400 ppm and 3900 ppm, respectively, according to the method of Johnson and Nishita (1952). This soil was formed on acid till, high in sulphur content, derived from marine shale (Clark and Green, 1964). Tills containing some material similar to this seem to be associated with the more acid soils in the Peace River area in Alberta and British Columbia and in the Lac La Biche-Plamondon area in Alberta.

The areas in Alberta and the Peace River area in British Columbia where acid soils are a problem should be thoroughly examined to determine the pH and soluble aluminum levels in topsoils and subsoils and otherwise rate the soil for agricultural productivity. Current soil surveys have separated groups of soils on the basis of soil series and topography. However, the older surveys did not give much consideration to the chemical nature of the tills as a basis for forming soil series. As a result the acid, sulphur-containing tills, referred to by Clark and Green (1964), are not clearly mapped out. These high sulphur, marine-deposited materials are present in the areas where high levels of aluminum are found. Even in the more recent surveys soil pH is highly variable within series and soluble aluminum is not considered as a basis for soil classification. The "Grandin" series in the Lac La Biche area is easily identifiable and uniformly quite acid. Other soil series which contain acid soils appear to be quite variable.

Any improvement in crop productivity and in land use involving liming, crop variety selection, and removal of lands from cultivation would require individual consideration of fields. The soils with only acid surface horizons and little or no amounts of soluble aluminum in

the subsoils could be limed in the plow layer. Those soils with quite acid subsoils would be best suited to growth of aluminum-tolerant crops such as oats or timothy or varieties of other crops which have been selected for aluminum tolerance. Liming of the plow layer would also benefit soil with quite acid subsurface horizons if they were in areas where rainfall was sufficient in the growing season to maintain a crop which obtained its moisture requirements primarily from the surface horizons. The most severely acid soils should probably be removed from cultivation because very large amounts of lime are needed for surface horizons alone and the problem of subsoil acidity would still remain.

Lands opened up for agricultural development in Alberta were chosen on the basis of soil criteria other than soil pH at least until the latter half of the 1960s. In Alberta little crown land with acidity problems has been released for agriculture recently simply because Alberta government policy since 1960 has been to release very little crown land. However, in the Peace River block in British Columbia large areas of land have been cleared for agricultural use and this only ceased in 1972 and 1973. Chemical factors of soils were not given much consideration in this land development program. Many areas were opened by large developers because they could show profit on a tax loss, capital gain basis. This has no longer been feasible since the change in tax laws in 1972 resulting in the restriction of tax write-off of losses of business enterprises against profits from another business enterprise and the imposition of a capital gains tax. Because of Canadian Wheat Board regulations restricting sale of feed grains across provincial borders, British Columbia was a deficit area for feed grains. Oats

could be grown on more acid soils and easily sold at a good price in the lower Fraser Valley area. Now with the Canadian Wheat Board in 1973 allowing competitive marketing of feed grains across provincial borders the economic viability of the less productive soils is in doubt if the current high prices of feed grains should decline.

CONCLUSIONS

A number of conclusions were formed regarding the characteristics and management of acid soils from the Boreal Forest regions of Alberta and northeastern British Columbia.

1. Root penetration of alfalfa and barley is restricted by subsoil acidity. This reduction of root development causes a reduction in top growth. The restricted root penetration which occurs in an unlimed subsoil and the aluminum toxicity which interferes with root metabolism results in reduced uptake of water from the subsoil. Water use is a sensitive indicator of amount of root development and of the impairment of root function which may occur in an acid subsoil. This reduction in yield of crops by the presence of an acid subsoil is in contradiction to evidence in the literature which suggests subsoil acidity restricts root penetration but does not reduce crop yield.

2. Subsoil acidity can be overcome by lime applications to the subsoil or its effects can be overcome by very large applications of phosphorus to the subsoil. Neither of these methods is economically feasible. Phosphorus fertilization rates should be tested specifically on acid soils along with surface applications of lime in order to determine the most economical optimum level of both phosphorus and lime to improve crop growth on acid soils.

3. A preliminary soil survey indicated that there are major areas in Alberta and northeastern British Columbia where soil acidity and subsoil acidity exist at levels sufficient to cause major impairment of growth of crop varieties which are sensitive to aluminum toxicity. Soil pH and soluble aluminum values from the field survey indicate the

15-30 cm layer often has the lowest pH and the highest levels of soluble aluminum. A number of the profiles examined show that quite low pH values and toxic levels of aluminum occur at depths up to one meter or more. Soil acidity was found to be quite variable within soil series and in many areas currently defined soil series do not give an indication of problem acid areas. Further work is needed to determine the areas in Alberta and British Columbia where acid surface soils and subsoils exist and have toxic levels of aluminum and perhaps manganese. Further lands being considered for clearing for agricultural use in Alberta and northeastern British Columbia should be examined for acidity and toxic levels of aluminum and manganese in surface soils and aluminum in subsoils.

4. Soil pH, levels of aluminum soluble in 0.02M $CaCl_2$, and levels of aluminum exchangeable in 1M KCl in the subsoil were found to give good correlations with the impairment of root penetration of alfalfa and barley in acid soils. Soluble aluminum was the best indicator of impairment of root development on acid soils. Some restriction in root development was evident when soluble aluminum levels were less than 3 ppm and the subsoil root yield of alfalfa was reduced by about 50 per cent when aluminum levels in the subsoil were at 20 ppm. Soil manganese did not show any relationship to root development of alfalfa in the subsoils. Soil manganese levels in the subsoils were much lower than in the topsoils.

5. Crop damage by soil acidity was not greatly intensified by low temperatures. Therefore crops grown on acid soils in the greenhouse at normal greenhouse temperatures should give results which are applicable to field conditions where soil temperatures are normally much lower.

6. Growth of crops tolerant to the toxic factors of subsoil acidity is the best means of managing soils with acid subsoils. In most cases this toxic factor is soluble aluminum. Some work was done to screen barley varieties for differences in aluminum tolerance and it was found that differences do exist among barley varieties grown in Alberta. These differences are not as large as differences in aluminum tolerances of barley varieties reported in the literature in USA with other barley varieties. This suggests a need for plant breeding work to incorporate genes for aluminum tolerance into the barley varieties which are adapted to conditions in Alberta and northeastern British Columbia. Further work is needed on screening presently used varieties of barley and other crops for aluminum tolerance.

REFERENCES CITED

ABBOT, J.B., CONNOR, S.D., SMALLEY, H.R. 1913. Soil acidity nitrification and the toxicity of soluble salts of aluminum. Pub. by Purdue University Agricultural Experimental Station. Bulletin No. 170, XVII: 329-373.

ADAMS, F., PEARSON, R.W. 1967. Crop response to lime in the southern United States and Puerto Rico. In: Soil Acidity and Liming. Ed. by R.W. Pearson, F. Adams. Amer. Soc. of Agronomy. Madison. pp. 161-206.

ARNON, D.I., JOHNSON, C.M. 1942. Influence of hydrogen ion concentration on the growth of higher plants under controlled conditions. Plant Physiology. 17: 525-539.

BARBER, S.A. 1967. Liming materials and practices. In: Soil Acidity and Liming. Edited by R.W. Pearson, F. Adams. American Society of Agronomy. Madison. pp. 125-160.

BLUME, H.P., SCHWERTMAN, U. 1969. Genetic evaluation of profile distribution of aluminum, iron, and manganese oxides. Soil Sci. Soc. Amer. Proc. 33: 438-444.

BONNER, J. 1965. Development from Plant Biochemistry. Edited by J. Bonner, J.E. Varner. Academic Press. New York. pp. 850-866.

BRADFIELD, R. 1923. The nature of the acidity of colloidal clay of acid soils. Journal of American Chem. Soc. 45: 2669-2678.

CHENG, B.T., BOURGET, S.J., OUELLETTE, G.J. 1971. Effect of some soil physical properties on growth and manganese, iron, aluminum, and molybdenum content of oats. Can. Journal Soil Sci. 51: 125-127.

CHENERY, E.M. 1948. Thioglycolic acid as an inhibitor to iron in the colorimetric determination of aluminum by means of aluminum. Analyst. 73: 501-502.

CLARK, J.S., GREEN, A.J. 1964. Some characteristics of Grey soils of low base saturation from northeastern British Columbia. Can. Journal Soil Sci. 44: 319-328.

CLARK, R.B., BROWN, J.C. 1973. Differential phosphorus uptake by phosphorus stressed maize inbreds. Unpubl. data from USDA, Beltsville.

CLARKSON, D.T. 1966. Aluminum tolerance in species within the genus *Agrostis*. Journal of Ecology. 54: 167-168.

CLARKSON, D.T. 1967. Interactions between aluminum and phosphorus on root surfaces and cell wall material. Plant and Soil. 27: 347-356.

CLARKSON, D.T. 1968. Metabolic aspects of aluminum toxicity and some possible mechanisms for resistance. In: Ecological Aspects of the Mineral Nutrition of Plants. Edited by I.H. Rorison. Blackwell Scientific Publications. Oxford. pp. 381-412.

COLEMAN, N.T., HARWARD, M.E. 1953. The heats of neutralization of acid clays and cation exchange resins. Journal Amer. Chem. Soc. 75: 6045-6056.

COLEMAN, N.T., THOMAS, G.W. 1967. Basic chemistry of soil acidity. In: Soil Acidity and Liming. Edited by R.W. Pearson, F. Adams. Amer. Soc. of Agronomy. Madison. pp. 1-42.

CORMACK, R.G.H. 1962. Development of root hairs in angiosperms. Bot. Rev. 28: 446-464.

DALTON, F.N., RAWLINGS, S.L. 1966. Design criterial Peltier-effect thermocouple psychrometers. US Soil Salinity Lab. Soil Water Cons. Research Division. Agriculture Research Service, USDA. Pub. no. 438.

DEKOCK, P.C., INKSON, R.H.E. 1962. Manganese content of mustard leaves in relation to iron and major nutrient supply. Plant and Soil, 13: 183-190.

DODGE, C.S., HIATT, A.J. 1972. Relation of pH to ion imbalance by varieties of wheat (*Triticum vulgare*). Agron. Journal. 64: 476-481.

ESTRADA, J., CUMMINGS, G.A. 1968. Effects of lime and phosphorus treatments in specific horizons of acid soil on growth and chemical content of corn (*Zea mays* L.) Agronomy Journal. 60: 447-450.

FOY, C.D., BROWN, J.C. 1964. Toxic factors in acid soils: II. Differential aluminum tolerance of plant species. Soil Sci. Soc. Amer. Proc. 28: 27-32.

FOY, C.D., FLEMING, A.L., BURNS, C.R., ARMIGER, W.H. 1967. Characterization of differential Al tolerance among varieties of wheat and barley. Soil Sci. Amer. Proc. 31: 513-521.

FOY, C.D., FLEMING, A.L., GERLOFF, G.C. 1972. Aluminum tolerance in snap beans. Agron. Journal. 64: 815-818.

FOY, C.D., FLEMING, A.L., SCHWARTZ, J.W. 1973. Opposite aluminum and manganese tolerances of two wheat varieties. Agron. Journal. 65: 123-126.

GRIME, J.P., HODGSON, J.G. 1968. The ecological significance of lime. In: Ecological Aspects of the Mineral Nutrition of Plants. Ed. by I.H. Rorison. Blackwell Scientific Publications. Oxford. pp. 67-100.

HARTWELL, B.L., PEMBER, F.R. 1918. The presence of aluminum as a reason for the difference in the effect of a so called acid soil on barley and rye. Soil Sci. 6: 259-277.

HEWITT, E.J., GRUNDY, C.S. 1970. The molybdenum requirements of plants in relation to nitrogen supply. Journal of Hort. Sci. 45: 351-357.

HOURIGAN, W.R., FRANKLIN, R.E., McLEAN, E., BHUMBLA, D.R. 1961. Growth and Ca uptake of plants as effected by rate and depth of liming. Soil Sci. Soc. Amer. Proc. 25: 491-494.

HOYT, P.B., NYBORG, M. 1971. Toxic metals in acid soil. I. Estimation of plant available aluminum. Soil Sci. Soc. Amer. Proc. 35: 236-240.

HOYT, P.B., NYBORG, M. 1971a. Toxic metals in acid soils. II. Estimation of plant available manganese. Soil Sci. Soc. Amer. Proc. 35: 241-244.

HSU, P.H. 1963. The effect of initial phosphate and silicate on the determination of aluminum with aluminon. Soil Sci. 96: 230-238.

IVANOVA, N.N. 1973. Molybdenum in plant nutrition. Agrochemica. 17: 96-118.

JACKSON, W.A. 1967. Physiological effects of soil acidity. In: Soil Acidity and Liming. Edited by R.W. Pearson, F. Adams. Amer. Soc. of Agronomy. Madison. 12: 43-124.

JOHNSON, C.M., NISHITA, H. 1952. Microestimation of sulphur in plant materials, soils, and irrigation waters. Anal. Chem. 24: 736-742.

KERRIDGE, P.C., DAWSON, M.D., MOORE, D.P. 1971. Separation of degrees of aluminum tolerance in wheat. Agronomy Journal. 63: 586-591.

LANCE, J.C., PEARSON, R.W. 1969. Effect of low concentrations of aluminum on growth, water, and nutrient uptake by cotton roots. Soil Sci. Soc. Amer. Proc. 33: 95-98.

LATHWELL, D.J., PEECH, M. 1965. Interpretation of chemical soil tests. New York. Cornell University. Agric. Exp. Bulletin No. 995.

LIN, C., COLEMAN, N.T. 1960. The measurement of exchangeable aluminum in soils and clays. Soil Sci. Soc. Amer. Proc. 24: 444-446.

LONG, F.L., FOY, C.D. 1972. Plant varieties as indicators of aluminum toxicity. Agronomy. 62: 679-681.

LONG, F.L., LANGDALE, G.W., MYHRE, D.L. 1973. Response of an aluminum tolerant and an aluminum sensitive genotype to lime, P and K on three Atlantic Coast Flatwoods soils. Agronomy. 65: 30-34.

LONGNECKER, D., MERKLE, F.G. 1952. Influence of placement of lime compounds on root development and soil characteristics. Soil Sci. 73: 71-74.

MAYO, J. 1970. Personal communication.

McCORMICK, L.H., BORDEN, F.Y. 1972. Phosphate fixation by aluminum in plant roots. Soil Sci. Soc. Amer. Proc. 36: 799-802.

McFARLANE'S GEOGRAPHICAL COLLECTIONS. 1683. An account of the northside coast of Buchan. Scot. Hist. Soc. 2: 140.

McKENZIE, R.C. 1970. Agricultural use of coal derived humic acids. Unpublished M.Sc. thesis. University of Alberta. Canada.

MOORE, D.P., JACOBSEN, L., OVERSTREET, R. 1961. Uptake of calcium by excised barley roots. Plant Physiology. 36: 53-57.

MORSE, F.W. 1915. The effect on a crop of clover of liming the soil. Mass. Agric. Exp. Station. Bulletin no. 161: 119-124.

OTA, Y., TANAKA, T. 1960. The physiological effect of iron on the rice plant. Proc. Crop Sci. Soc. Japan. 28: 367-370.

PEARSON, R.W., ABRUNA, F., VINCENTE-CHANDLER, J. 1962. Effect of lime and nitrogen on downward movement of calcium and magnesium in two humid tropical soils of Puerto Rico. Soil Sci. 93: 77-82.

PEARSON, R.W., ADAMS, F. 1967. Soil Acidity and Liming. Amer. Soc. of Agronomy. Madison.

PENNEY, D.C. 1973. Crop responses to liming on acid soils. An unpublished M.Sc. thesis. University of Alberta, Canada.

PIERRE, W.H. 1931. Hydrogen ion concentration, aluminum concentration in the soil solution and percentage base saturation as factors affecting plant growth on acid soils. Soil Sci. 31: 183-207.

RANDALL, P.J., VOSE, P.B. 1963. Effect of aluminum on uptake and translocation of phosphorus. Plant Physiology. 38: 403-413.

REEVE, N.G., SUMNER, M.E. 1970. Lime requirements of Natal oxisols based on exchangeable aluminum. SSSAP. 34: 595-598.

REEVE, N.G., SUMNER, M.E. 1972. Amelioration of subsoil acidity in Natal oxisols by leaching of surface applied amendments. Agrochemophysica. 4: 1-6.

RICHBURG, J.S., ADAMS, F. 1970. Solubility and hydrolysis of aluminum in soil solutions and saturated paste extracts. Soil Sci. Soc. Amer. Proc. 34: 728-734.

REID, D.A., FLEMING, A.L., FOY, C.D. 1971. A method for determining aluminum response of barley in nutrient solution in comparison to response in Al-toxic soil. Agronomy Journal. 63: 600-603.

RIOS, M.A., PEARSON, R.W. 1964. The effect of some chemical environmental factors on cotton root behavior. Soil Sci. Soc. Amer. Proc. 28: 232-235.

RUPRECHT, R.W. 1915. Toxic effect of iron and aluminum salts on clover seedlings. Massachusetts Agricultural Exp. Station. Bulletin no. 161: 125-129.

SAMPSON, M., CLARKSON, D.T., DAVIES, D. 1965. DNA synthesis in aluminum-treated roots of barley. Science. 148: 1476-1477.

SCHMEHL, W.R., PEECH, M., BRADFIELD, R. 1950. Causes of poor growth of plants on acid soils and beneficial effects of liming: I. Evaluation of factors responsible for acid soil injury. Soil Sci. 70: 393-410.

SHEAT, D.E., FLETCHER, B.H., STREET, H.F. 1959. Studies on the growth of excised roots. The growth of excised tomato roots supplied with various inorganic sources of nitrogen. New Phytology. 58: 128-141.

SUTTON, C.D., HALLSWORTH, E.G. 1958. The toxicity of low pH and high manganese to lucerne as affected by climatic factors and calcium supply. Plant and Soil. 9: 305-317.

VIETCH, F.P. 1902. The estimation of soil acidity and lime requirements of soils. Journal of Amer. Chem. Soc. 24: 1120-1128.

WALLER, R.A., DUNCAN, D.B. 1969. A Bayes Rule for the symmetric multiple comparisons problem. Journal of the Amer. Statistical Association. 64: 1484-1503.

WOOLHOUSE, H.W. 1968. The acid phosphatases of plant roots. In: Ecological aspects of the mineral nutrition of plants. Edited by I.H. Rorison. Blackwell Scientific Publications. Oxford. 357-380.

APPENDIX I

Legal Locations, Chemical Data, and Liming Rates for Soils from Field Plots

Site	Legal location	Depth	pH	ppm of 0.02M $CaCl_2$ soluble Al	Mn	ppm of 1M KCl exchangeable Al	Ca	Mg	Na	Lime added ppm $Ca(OH)_2$
Silver Valley	NE 10-82-10-6	0-12.5	4.4	51	2.0	700	825	98	125	8000
		12.5-25	4.2	90	1.6	1050	900	128	138	6250
		25-50	4.0	95	1.4	925	1050	155	150	5500
Bessborough	SW 2-79-17-6	0-12.5	4.9	-	-	75	1725	240	125	2400
		12.5-25	4.8	9.9	3.0	150	1450	213	68	2250
		25-50	4.8	14.5	0.7	500	1550	233	88	3750
Plamondon	NW 19-67-15-4	0-12.5	5.0	3.4	24	-	100	188	1450	1200
		12.5-25	4.6	24.9	6.2	650	150	813	850	1650
		25-50	4.6	20.0	1.5	625	313	1188	1175	2400
Evansburg	NW 32-53- 7-5	0-12.5	5.3	0.9	0.8	8	3275	815	108	3400*
		12.5-25	4.7	4.9	1.8	50	3325	850	110	16000*
		25-50	4.6	5.1	1.2	300	4300	1275	133	17000*
Valleyview	SW 29-69-22-5	0-12.5	5.6	1.0	8.0	21	1900	308	125	3200*
		12.5-25	5.2	4.7	3.6	400	2275	745	288	3750*
		25-50	4.8	7.5	1.7	450	3125	1145	363	4000*

* ppm of lime added as $CaCO_3$

APPENDIX II

Root Yields and Soil Moisture Data for Field Experiments from Plots Dug to 50 cm and Limed to 12.5 cm and Plots Dug to 50 cm, Limed to 50 cm

Root Yields*(in g) from Alfalfa Plots at Silver Valley, September, 1971.

	Limed to 12.5 cm					Limed to 50 cm				
Depth	Rep 1	Rep 2	Rep 3	Rep 4	Average	Rep 1	Rep 2	Rep 3	Rep 4	Average
0-12.5 cm	4.84	6.61	6.93	5.12	5.875	7.23	3.34	3.68	3.74	4.498
12.5-25 cm	0.070	0.036	0.009	0.000	0.029	1.93	0.348	2.13	0.264	1.168
25-37.5 cm	0.000	0.000	0.000	0.000	0.000	0.74	0.380	0.760	0.052	0.483
37.5-50 cm	0.000	0.000	0.000	0.000	0.000	0.034	0.010	0.014	0.005	0.016

Soil Moisture (%) from Alfalfa Plots at Silver Valley, September, 1971.

	Limed to 12.5 cm					Limed to 50 cm				
Depth	Rep 1	Rep 2	Rep 3	Rep 4	Average	Rep 1	Rep 2	Rep 3	Rep 4	Average
0-12.5 cm	17.13	20.40	19.09	17.52	18.54	16.81	-	18.12	17.91	17.61
12.5-25 cm	23.03	23.40	25.69	22.19	23.58	19.52	18.53	19.00	20.45	19.38
25-37.5 cm	26.72	25.03	-	21.10	24.28	19.11	20.18	18.84	19.57	19.43
37.5-50 cm	29.71	26.42	28.73	24.60	27.37	26.58	24.48	20.87	21.53	23.37

* Root yields in grams from three soil cores, each 5 cm in diameter.

APPENDIX II. (continued)

Root Yields (in g) from Barley Plots at Silver Valley, September, 1971.

Depth	Limed to 12.5 cm					Limed to 50 cm				
	Rep 1	Rep 2	Rep 3	Rep 4	Average	Rep 1	Rep 2	Rep 3	Rep 4	Average
0-12.5 cm	0.760	0.741	0.613	0.584	0.675	0.580	0.972	0.717	0.584	0.713
12.5-25 cm	0.288	0.082	0.000	0.000	0.093	0.042	0.073	0.065	0.125	0.076
25-37.5 cm	0.000	0.000	0.000	0.000	0.000	0.015	0.015	0.024	0.003	0.014
37.5-50 cm	0.000	0.000	0.000	0.000	0.000	0.002	0.006	0.003	0.011	0.005

Soil Moisture (%) from Barley Plots at Silver Valley, September, 1971.

Depth	Limed to 12.5 cm					Limed to 50 cm				
	Rep 1	Rep 2	Rep 3	Rep 4	Average	Rep 1	Rep 2	Rep 3	Rep 4	Average
0-12.5 cm	25.30	26.12	22.37	25.87	24.92	23.01	21.21	18.13	22.17	21.13
12.5-25 cm	28.34	26.51	29.42	25.66	27.48	24.50	21.89	21.60	23.25	22.81
25-37.50 cm	29.30	26.32	31.24	25.33	28.05	23.93	23.16	22.12	22.03	22.80
37.5-50 cm	28.08	26.87	25.91	24.17	26.26	28.17	26.66	26.39	26.62	26.96

Root Yields (in g) from Alfalfa Plots at Bessborough, September, 1971.

Depth	Limed to 12.5 cm					Limed to 50 cm				
	Rep 1	Rep 2	Rep 3	Rep 4	Average	Rep 1	Rep 2	Rep 3	Rep 4	Average
0-12.5 cm	3.23	2.96	3.17	2.78	3.035	1.880	2.82	1.95	2.13	2.195
12.5-25 cm	0.733	0.628	0.813	0.805	0.745	0.417	0.733	0.374	0.397	0.480
25-37.5 cm	0.033	0.052	0.122	0.154	0.090	0.098	0.276	0.159	0.128	0.165
37.5-50 cm	0.000	0.000	0.008	0.000	0.002	0.024	0.053	0.024	0.002	0.026

APPENDIX II. (continued)

Soil Moisture (%) from Alfalfa Plots at Bessborough, September, 1971.

Depth	Limed to 12.5 cm					Limed to 50 cm				
	Rep 1⊕	Rep 2	Rep 3⊕	Rep 4	Average	Rep 1⊕	Rep 2	Rep 3⊕	Rep 4	Average
0-12.5 cm	-	13.25	-	14.06	13.66	-	13.96	-	6.42	10.19
12.5-25 cm	-	15.58	-	11.39	13.49	-	15.70	-	19.70	17.70
25-37.5 cm	-	27.05	-	24.99	26.02	-	21.48	-	23.17	22.33
37.5-50 cm	-	32.43	-	28.35	30.39	-	22.05	-	22.88	22.47

Root Yields (in g) from Barley Plots at Bessborough, September, 1971.

Depth	Limed to 12.5 cm					Limed to 50 cm				
	Rep 1	Rep 2	Rep 3	Rep 4	Average	Rep 1	Rep 2	Rep 3	Rep 4	Average
0-12.5 cm	0.282	0.303	0.419	0.190	0.299	0.381	0.257	0.281	0.327	0.313
12.5-25 cm	0.132	0.193	0.175	0.042	0.136	0.053	0.062	0.034	0.061	0.053
25-37.5 cm	0.005	0.000	0.004	0.010	0.005	0.027	0.018	0.008	0.068	0.030
37.5-50 cm	0.000	0.000	0.000	0.000	0.000	0.020	0.026	0.029	0.010	0.021

Soil Moisture (%) from Barley Plots at Bessborough, September, 1971.

Depth	Limed to 12.5 cm					Limed to 50 cm				
	Rep 1	Rep 2	Rep 3	Rep 4	Average	Rep 1	Rep 2	Rep 3	Rep 4	Average
0-12.5 cm	14.31	11.35	14.10	14.40	13.54	13.87	12.76	14.32	12.83	13.45
12.5-25 cm	12.80	16.32	14.70	13.21	14.26	16.94	14.08	14.40	18.28	15.95
25-37.5 cm	24.85	28.15	22.52	23.38	24.73	19.27	15.91	17.85	15.32	17.09
37.5-50 cm	28.17	29.78	24.86	27.22	27.51	19.72	18.57	16.63	19.59	19.13

⊕ not sampled.

APPENDIX II. (continued)

Root Yields (in g) from Alfalfa Plots at Plamondon, September, 1971.

Depth	Limed to 12.5 cm					Limed to 50 cm.				
	Rep 1	Rep 2 ⊕	Rep 3	Rep 4	Average	Rep 1	Rep 2 ⊕	Rep 3	Rep 4	Average
0-12.5 cm	2.495	-	4.53	7.700	4.908	3.273	-	3.533	7.42	4.742
12.5-25 cm	1.500	-	1.023	1.755	1.426	0.815	-	1.284	1.445	1.181
25-37.5 cm	0.065	-	0.217	0.971	0.418	0.176	-	0.525	0.579	0.427
37.5-50 cm	0.000	-	0.037	0.127	0.055	0.052	-	0.121	0.154	0.109

Soil Moisture (%) from Alfalfa Plots at Plamondon, September, 1971.

Depth	Limed to 12.5 cm					Limed to 50 cm				
	Rep 1	Rep 2 ⊕	Rep 3	Rep 4	Average	Rep 1	Rep 2 ⊕	Rep 3	Rep 4	Average
0-12.5 cm	7.65	-	6.70	5.59	6.65	7.12	-	6.00	7.29	6.80
12.5-25 cm	12.85	-	9.35	8.09	10.10	11.46	-	11.24	9.51	10.74
25-37.5 cm	22.38	-	18.83	14.37	15.19	17.92	-	15.46	17.31	16.90
37.5-50 cm	26.04	-	22.42	19.70	22.72	18.21	-	15.48	17.36	17.02

Root Yields (in g) from Barley Plots at Plamondon, September, 1971

Depth	Limed to 12.5 cm					Limed to 50 cm				
	Rep 1	Rep 2 ⊕	Rep 3	Rep 4	Average	Rep 1	Rep 2 ⊕	Rep 3	Rep 4	Average
0-12.5 cm	0.319	-	0.536	0.518	0.458	0.337	-	0.462	0.397	0.399
12.5-25 cm	0.047	-	0.063	0.181	0.097	0.115	-	0.161	0.075	0.117
25-37.5 cm	0.008	-	0.005	0.007	0.007	0.060	-	0.184	0.046	0.097
37.5-50 cm	0.000	-	0.004	0.004	0.003	0.033	-	0.062	0.024	0.040

⊕ not sampled.

APPENDIX II. (continued)

Soil Moisture (%) from Barley Plots at Plamondon, September, 1971.

	Limed to 12.5 cm					Limed to 50 cm				
Depth	Rep 1	Rep 2	Rep 3	Rep 4	Average	Rep 1	Rep 2	Rep 3	Rep 4	Average
0-12.5 cm	12.2	10.4	8.5	7.0	9.6	8.9	16.8	6.2	9.2	10.3
12.5-25 cm	15.2	10.5	14.3	11.9	13.0	10.8	16.6	11.3	11.0	12.5
25-37.5 cm	26.4	23.9	24.4	21.5	24.1	16.5	20.1	15.9	17.6	17.6
37.5-50 cm	29.0	21.8	25.1	24.5	25.1	18.0	18.9	17.3	19.5	18.5

Root Yields (in g) from Barley Plots at Evansburg, September, 1972.

	Limed to 12.5 cm					Limed to 50 cm				
Depth	Rep 1	Rep 2	Rep 3	Rep 4	Average	Rep 1	Rep 2	Rep 3	Rep 4	Average
0-12.5 cm	0.430	0.321	0.328	0.285	0.341	0.699	0.397	0.384	0.640	0.530
12.5-25 cm	0.034	0.079	0.054	0.056	0.056	0.070	0.052	0.035	0.050	0.052
25-37.5 cm	0.037	0.017	0.016	0.054	0.031	0.037	0.032	0.028	0.054	0.038
37.5-50 cm	0.036	0.016	0.005	0.000	0.014	0.070	0.025	0.027	0.074	0.049

Soil Moisture (%) from Barley Plots at Evansburg, September, 1972.

	Limed to 12.5 cm					Limed to 50 cm				
Depth	Rep 1	Rep 2	Rep 3	Rep 4	Average	Rep 1	Rep 2	Rep 3	Rep 4	Average
12.5-25 cm	25.4	29.0	28.5	27.7	27.7	22.8	32.1	31.0	29.0	28.7
25-37.5 cm	29.1	29.7	30.5	33.0	30.6	28.3	31.1	30.6	28.5	29.6
37.5-50 cm	27.2	28.1	29.4	31.9	29.2	29.5	29.6	31.0	28.4	29.6

APPENDIX II. (continued)

Root Yields (in g) from Barley Plots at Valleyview, 1972.

Depth	Limed to 12.5 cm					Limed to 50 cm				
	Rep 1	Rep 2	Rep 3	Rep 4	Average	Rep 1	Rep 2	Rep 3	Rep 4	Average
0-12.5 cm	0.57	0.49	0.73	0.33	0.53	0.76	0.85	0.34	0.59	0.64
12.5-25 cm	0.169	0.070	0.122	0.116	0.119	0.084	0.118	0.082	0.055	0.085
25-37.5 cm	0.110	0.076	0.124	0.104	0.104	0.077	0.082	0.065	0.092	0.079
37.5-50 cm	0.061	0.022	0.063	0.046	0.048	0.054	0.033	0.037	0.054	0.045

Moisture in the Soil (%) from Barley Plots at Valleyview, 1972.

Depth	Limed to 12.5 cm					Limed to 50 cm				
	Rep 1	Rep 2	Rep 3	Rep 4	Average	Rep 1	Rep 2	Rep 3	Rep 4	Average
12.5-25 cm	15.6	20.1	17.5	13.9	16.8	15.6	18.1	18.3	14.8	16.7
25-37.5 cm	21.5	24.6	17.5	17.8	20.4	19.7	18.2	22.0	19.2	19.8
37.5-50 cm	21.3	23.8	21.8	19.9	21.7	20.7	22.9	20.4	20.4	21.1

APPENDIX III

Analytical Data and Classification for Soil Cores from the Field Survey on Subsoil Acidity

Soil series	Legal location	0-15 cm			15-30 cm			45-60 cm			90-110cm
		pH*	Al**	Mn**	pH	Al	Mn	pH	Al	Mn	pH
Mapova	NW 27-61-20-4	7.9			7.9			lime			lime
Athabasca	NE 20-64-20-4	5.75	0.0		4.6	7.1		6.1			lime
	SW 6-65-18-4	6.4			5.1	0.4		4.9	0.6		4.95
Edward	SE 24-65-18-4	6.2			5.4	2.5		5.35	2.1		6.6
Athabasca	NW 15-65-17-4	7.0			6.5			5.5	0.0		5.6
Nestow	NW 11-66-17-4	6.1			4.5	6.8		5.85			5.9
Grosmont	SE 28-66-17-4	7.6			7.5			7.4			
Grosmont	NW 32-66-17-4	6.5			6.25			6.4			6.4
	NE 9-67-17-4	6.6			6.7			6.5			5.6
Athabasca	SE 23-67-17-4	6.55			6.55			5.8	0.0		6.6
Grandin	NE 22-67-16-4	6.05			4.95	16.5		4.13	35.4		4.05
Grandin	NE 23-67-16-4	5.65	0.0		4.4	15.1	0.3	4.65	2.5	1.2	6.7
Grandin	NW 22-67-15-4	5.05	8.2		4.4	50		4.1	39		4.1
Codessa	NE 23-67-15-4	6.6			6.65			6.55			5.85
Grandin	SE 24-67-15-4	6.5			5.05	3.2		4.5	7.2		5.45
Maywood	SE 2-67-14-4	6.8			6.6			7.6			lime
Athabasca	NW 9-66-14-4	6.8			6.1			lime			lime
	NW 9-66-14-4	6.6			5.6	1.3	1.3	5.1	2.2	1.1	7.2
Edward	SE 2-66-15-4	7.95			7.7			6.6			
Athabasca	SW 35-65-15-4	7.2			7.2			6.0			7.1
	SW 14-65-15-4	6.95			6.3			6.4			lime
Grandin	NW 36-66-16-4	6.4			5.65	0.4		5.4	0.7		lime
Grandin	SW 10-67-15-4	5.95			5.5	1.4		4.7	5.3		6.7
Grandin	SE 31-67-15-4	5.7	0.6		5.0	1.4		5.65	0.2		lime
Grandin	NW 26-67-16-4	6.05			5.0	11.6					7.1
Grandin	NE 19-67-15-4	5.35	1.6		4.9	15.5		4.5	13.0		7.6

* pH determined on 2.5 parts water and 1 part soil.
**0.02 M $CaCl_2$ soluble aluminum and manganese in ppm.

APPENDIX III (continued)

Soil series	Legal location	0-15 cm pH*	0-15 cm Al**	0-15 cm Mn**	15-30 cm pH	15-30 cm Al	15-30 cm Mn	45-60 cm pH	45-60 cm Al	45-60 cm Mn	90-110cm pH
Grandin	SE 19-67-15-4	5.6	1.2		4.8	14.2		4.7	4.2		7.2
	NW 23-67-18-4	6.15			5.5	0.8		6.0			6.2
Tolman	SE 35-67-19-4	6.7			5.6	0.6					6.6
Athabasca	NE 35-67-19-4	6.9			7.2			5.7	0.6		
Athabasca	SE 26-65-19-4	7.2			7.3			7.7			lime
	SW 32-60- 1-5	5.6	0.8		5.55	0.2		6.9			
	SW 7-61- 1-5	6.2			7.0			7.4			
	SE 28-61- 2-5	6.4			5.8	0.4		lime			
Heart	SE 31-61- 2-5	7.5			6.35			lime			
Heart	NE 8-63- 4-5	6.1			6.2			7.3			
Hubalta	SE 14-63- 5-5	6.6			6.9			lime			
Hubalta	NE 5-63- 5-5	7.0			8.0			8.4			8.4
Hubalta	NE 1-63- 6-5	8.0			stony						
Hubalta	SE 2-63- 6-5	6.1			5.4	1.2		6.0			
	NW 28-62- 6-5	6.0			5.8	0.6		5.25	3.6		stony
	SE 22-62- 8-5	6.1			5.95			stony			
	SE 28-61- 9-5	6.5			6.15			5.6	0.6		lime
	NE 12-61- 9-5	6.9			7.7			8.0			8.1
	NE 32-60- 9-5	5.8			5.65	0.4		7.9			
Donnelly	NE 10-66-21-5	5.8	0.0		5.7	0.4		5.65	0.6		
Donnelly	NE 17-66-21-5	6.5			6.55			7.0			7.3
Donnelly	SE 27-67-22-5	5.75	0.6		5.45	2.4		5.75	1.0		8.2
Donnelly	SE 34-68-22-5	5.45	3.1		5.1	8.6		5.2	5.2		7.9
Esher	NW 15-68-22-5	5.65	1.0		5.4	1.0		5.4	1.0		7.8
	NW 34-68-22-5	6.9			5.25	4.2		5.35	2.5		
Donnelly	SW 29-69-22-5	5.7	0.8		4.2	7.0		5.6			7.6
	SW 12-71-22-5	5.15	1.0		4.7	4.0		6.5			7.7
Donnelly	SW 33-71-22-5	4.9	7.1		5.1	8.0		5.0			7.8
	SW 10-70-22-5	5.5	2.0		5.15	9.0		7.7			8.2

* pH determined on 2.5 parts water and 1 part soil.
**0.02 M $CaCl_2$ soluble aluminum and manganese in ppm.

APPENDIX III (continued)

Soil series	Legal location	0-15 cm			15-30 cm			45-60 cm			90-110cm
		pH	Al	Mn	pH	Al	Mn	pH	Al	Mn	pH
Esher	NE 28-69-22-5	6.0			5.95	0.2		6.85			lime
Snipe	SE 21-69-22-5	6.05			5.55	1.0		6.8			7.9
	NW 13-61-15-5	6.3			5.85	0.6		5.8	0.6		lime
	NE 19-60-13-5	6.05			5.7	0.6		5.95			lime
	NE 8-59-11-5	5.2	1.0		5.85	0.6		6.05			
	SE 1-10-59-5	8.0			8.0			7.0			
	NE 16-58- 9-5	7.5			6.5			8.1			8.2
	NW 12-57- 8-5	6.0			5.1	3.0		7.0			7.5
Donnelly	SW 34-70-25-5	6.75			5.9	0.8		7.0			
	SE 17-71-25-5	6.25			6.15			5.85	0.4		lime
	NW 24-71-26-5	5.95	0.2		5.7	0.4		5.95	0.2		lime
Donnelly	SW 8-72-26-5	6.25			5.95	0.8		5.35	4.3		lime
Codessa	SE 12-72- 2-6	6.5			6.5			5.8	0.4		lime
Valleyview	SW 15-72- 4-6	5.85	0.4		6.7			lime			
	NW 12-74-12-6	6.25			5.5	1.2		6.5			
Hazelmere	SW 31-74-12-6	5.75			5.4	6.9		6.4			
Hazelmere	NE 25-74-12-6	5.35	2.5		5.35	5.6		5.7	1.0		lime
	SE 7-75-13-6	7.65			6.75			5.55			
Alcan	SW 19-78-16-6	4.9	10.0		4.95	21.0		5.0	4.0		6.5
Alcan	SE 36-78-17-6	5.9			5.6			4.85	9.2		4.65
	SW 2-79-17-6	5.3	1.4		5.5	6.0					
	NE 3-79-17-6	5.6	1.8		5.3	3.2		5.5	1.4		5.6
	SW 35-79-17-6	6.05			6.6			7.1			
Alcan	SE 3-80-17-6	6.8			6.45			5.7	1.0		5.6
Donnelly	SE 2-80-17-6	6.8			7.6			6.6			lime
Alcan	NW 11-80-17-6	7.6			4.75	6.8		4.9	4.0		lime
Alcan	NW 22-79-16-6	5.7	0.6		5.3	5.6		5.4	2.4		
Murdale	NW 15-79-16-6	5.9	0.6		5.65	0.4		5.55	2.2		7.7
Braeburn	NW 11-79-12-6	5.7	1.4		5.45	8.0		6.0			lime
Donnelly	NW 31-79-11-6	5.4	6.0		5.4	9.0		5.4	4.9		lime
Snipe	SW 17-80-11-6	6.05			5.4	1.5		6.2			lime
Priestville	SW 8-81-11-6	5.95			7.0			7.3			

APPENDIX III (continued)

Soil series	Legal location	0-15 cm pH	0-15 cm Al	0-15 cm Mn	15-30 cm pH	15-30 cm Al	15-30 cm Mn	45-60 cm pH	45-60 cm Al	45-60 cm Mn	90-110 cm pH
Snipe	NW 14-81-11-6	6.3			5.9	0.6		5.45	2.0		
Goose	SE 29-81-10-6	6.05			5.7	0.6		lime			
Josephine	NE 10-82-10-6	4.5	51.0	2.0	4.18	85.0	1.2	3.89	75.0	1.2	3.56
Boundary	SW 23-82-10-6	6.45			6.3			5.9	0.6		8.0
Boundary	SE 26-82-10-6	6.3			5.55	2.2		6.6			
Donnelly	NW 23-82-10-6	6.4			5.85	1.3		5.1	3.8		5.5
Donnelly	SE 24-82-10-6	5.5	2.2		5.45	4.4		7.4			
Snipe	SW 17-82- 9-6	5.9	0.6		5.4	9.0	1.2	lime			lime
	SW 12-82-10-6	5.5	1.8		5.35	6.4		8.0			
Donnelly	NE 34-81- 9-6	6.4			5.05	2.8		8.1			
Esher	SW 1-82- 9-6	6.0			5.65	2.2		5.55	1.8		
Donnelly	NE 2-82- 9-6	5.95	0.0		5.4	3.8					
Snipe	NW 7-82- 8-6	6.0			6.0						
	SW 17-81-17-6	6.0			6.0			7.0			
	SW 19-81-17-6	6.3			6.2			5.3	1.2		7.8
	NW 6-82-17-6	6.7			6.25			6.5			
Alcan	NW 19-84-19-6	6.4			5.6	2.0		4.65	5.4	7.8	
	NW 35-84-20-6	5.95			6.2						
Alcan	SE 3-85-20-6	6.7			5.8	0.0		5.1	7.0		7.2
	NW 4-85-20-6	6.3			5.7	1.0		5.75	0.0		6.1
	SE 6-86-20-6	4.75	17.0		4.95	30.0		4.9	17.0		
Alcan	SE 16-86-20-6	5.8	0.2		5.35	6.2		6.5			
	SW 14-86-19-6	6.1			5.5	2.8		5.0	7.4		lime
	SE 6-87-18-6	5.85			4.8	6.2		4.5	8.0		7.25
Buick	SW 2-87-19-6	5.9	0.8		5.2	2.0		4.55	17.0		5.0
Alcan	NE 33-86-19-6	6.1			5.25	3.2		4.8	15.0		lime
Alcan	SW 4-87-19-6	6.25			5.55	0.4		5.2	2.8		5.35
	NW 31-86-19-6	5.6	0.4		5.2	17.0	0.8	4.7	16.0		4.7
Alcan	NE 14-86-21-6	4.8	11.0		4.7	36.0		4.95	10.0		
Buick	SE 2-87-21-6	5.75	1.0		5.3	7.6					7.0
Alcan	NE Blk 35-88-21-6	6.0			4.5	11.0		7.6			

APPENDIX III (continued)

Soil series	Legal location	0-15 cm pH	0-15 cm Al	0-15 cm Mn	15-30 cm pH	15-30 cm Al	15-30 cm Mn	45-60 cm pH	45-60 cm Al	45-60 cm Mn	90-110cm pH
Alcan	SE Blk 8 Tp.111-6	6.6			5.7	1.0		4.9	10		6.8
	SW Blk 2606	5.45	1.6		4.85	20					6.7
Buick	SW Blk 2754	5.8	0.4		5.45	3.8		5.15	9.8		lime
	SE Blk 174	5.0	4.0		5.55	0.6		7.3			
	NE Blk 3124	4.75	14		5.6	0.4		7.0			
	NW Blk 3018	5.0	5.2		5.2	40		5.4	13		
	NE Blk 3018	5.7	1.2		5.35	3.0		6.7			
	SW Blk 173	4.9	27		4.8	30		4.9	12		
	NE Blk 2485	5.3	6.0		5.15	11					
	SW Blk 2485	5.3	5.0		5.3	5.0					
	NE Blk 2472	5.6	1.6	5.4	5.2	6.6					5.9
	SW Blk 856	5.2	6.0		5.5	2.2		6.5			7.7
	SW Blk 695	5.7	1.8	2.2	5.6	3.0	0.8	6.4			8.0
Snipe	NE 20-84-17-6	5.9	1.4	4.6	5.4	4.2		5.4	2.6		lime
	SE 26-84-17-6	5.5	2.8	11	5.4	5.0		6.1			lime
	SW 6-85-15-6	5.0	9.6		4.95	20		5.1	8.4		6.8
Snipe	NE 33-84-15-6	6.1			5.6	1.0	0.8	6.8			
Alcan	SW 1-85-15-6	6.05			5.0	13		4.95	13		6.8
Esher	NW 32-84-14-6	5.7	0.8	3.8	5.4	3.0		5.5	2.0		lime
	SW 36-84-14-6	6.75			5.5	1.6		5.3	3.0		lime
	SE 31-84-13-6	5.95			4.7	8.6		6.6			
	SW 27-85-12-6	5.7	0.9	10	5.5	2.2	0.8	5.6	1.5	0.8	5.7
	NE 3-87-11-6	5.6	1.6	2.0	5.5	2.0					7.6
Codessa	SE 19-87-10-6	5.6	1.2	9.8	4.8	20		5.0	10		8.0
Alcan	SE 19-87-10-6	6.15			5.1	8.2					7.0
Boundary	NW 34-87- 7-6	7.7			7.3						
Boundary	NW 34-87- 7-6	7.3			7.35			7.9			8.4
	SE 6-80-20-5	6.0			5.6	1.4		lime			lime
	SE 7-78-20-5	6.45			6.8			lime			
	SE 30-76-20-5	7.0			6.3			lime			
Codessa	NW 9-74-21-5	7.4			8.4			8.2			

APPENDIX III (continued)

Soil Series	Legal location	0-15 cm pH	0-15 cm Al	0-15 cm Mn	15-30 cm pH	15-30 cm Al	15-30 cm Mn	45-60 cm pH	45-60 cm Al	45-60 cm Mn	90-110cm pH
Snipe	SE 18-72-21-5	lime			lime						
Donnelly	SW 29-69-22-5	5.75	0.8	5.6	5.45	2.8		5.3	4.8		8.3
	SW 7-56- 7-5	6.6			5.8	0.2	1.0	5.55	0.8	2.8	7.6
Raven	SW 31-55- 7-5	5.7	0.8	3.6	5.45	1.6		lime			
	NE 1-55- 8-5	6.6			5.7	0.8	0.4	5.9			
Maywood	NE 24-54- 7-5	6.0			5.3	1.6		5.4	1.4		5.9
	NW 32-53- 7-5	5.6	1.0	6.0	4.9	4.6		5.9			7.8
	NW 33-38- 5-5	5.6	0.6	4.4	5.75	0.0	1.4	5.65	0.0	0.8	
	NW 8-41- 5-5	5.9	0.2	1.2	5.4	0.2	0.8	5.1	0.2	0.6	
	SE 6-41- 5-5	6.0			6.2			5.35	0.4	0.6	
	SE 24-37- 7-5	5.6	0.4	4.2	5.55	0.2	0.8	5.6	0.2	0.8	
	SE 2-38- 7-5	6.1			6.25			6.7			
	SW 34-37- 7-5	5.8	0.6	3.8	5.75	0.2	1.4	8.3			
	SW 15-39- 7-5	6.5			6.45			8.6			
	SW 34-40- 6-5	6.9			6.9			6.7			
	NW 22-41- 6-5	5.9	0.4	4.8	5.15	1.0	1.4	5.15	0.4	0.8	5.8
	SE 26-42- 4-5	6.3			5.7	0.2	0.6	4.7	1.4	0.6	6.0
	NE 23-42- 5-5	5.65	0.4	1.6	5.0	0.4	0.4	4.9	0.4	0.8	5.0
	SE 27-42- 5-5	5.85	0.2	0.4	6.0	0.2	0.4	5.1	0.2	0.8	5.9
	SW 27-42- 5-5	6.5			5.7	0.2	0.6	5.4	0.2	0.6	
	SW 11-43- 6-5	6.3			6.3			4.95	0.6	0.8	5.1
	NW 8-43- 6-5	6.3			6.3			5.1	1.4	1.2	5.0
Hubalta	SE 1-43- 5-5	6.4			5.3	0.2	0.6	6.0			
Hubalta	SW 23-43- 5-5	5.85	0.6	2.8	5.55	0.6	1.2	5.4	0.8	0.8	
	SW 7-45- 6-5	5.4			4.95			5.5			7.2
	SE 19-45- 6-5	6.2			6.1			6.2			
	SW 31-45- 6-5	6.6			6.3			6.3			
	NW 33-45- 6-5	6.25			4.8			4.85			
	NW 3-46- 6-5	5.65	0.4	3.6	5.25	2.8	0.8				
	SW 17-46- 4-5	6.0			6.1			8.6			
	SW 7-46- 3-5	6.9			6.6			6.0			

APPENDIX III. (continued)

Soil series	Legal location	0-15 cm pH	0-15 cm Al	0-15 cm Mn	15-30 cm pH	15-30 cm Al	15-30 cm Mn	45-60 cm pH	45-60 cm Al	45-60 cm Mn	90-110 cm pH	90-110 cm Al
	NE 10-46- 3-5	6.6			6.6			6.5				
	NW 8-46- 2-5	6.65			6.2							
	NE 15-59-14-4	6.5			5.9	0.8	0.6	5.6	0.8	1.4		
	SE 69-22- 5-5	5.5	2.2	12	5.25	11	2.6	5.85	0.8	2.0		
	SW 34-104-14-5	5.1	4.2	25	4.6	8.4	20	4.2	26	20		
	NE 35-104-14-5	4.3	12		3.85	44	29	3.76	62	30		
	SW 35-77- 3-6	5.5	3.2	3.0	6.50			7.9				
	NW 24-78- 8-6	5.4	2.2	10.0	5.5	5.0	0.6	7.8				
	SE 34-70- 8-6	6.1			6.0			7.9				
	SE 7-75-13-6	5.4			5.4			5.8				
	NW Blk 856	4.7			5.1	5.5	1.0	5.5	1.0	0.8		
	SE Blk 647	5.7	8.1	0.6	5.0	16	2.4	5.2	6.3	4.6		
	SW Blk 648	5.5			5.5	1.9	0.4	5.7	0.5	1.2		
Alcan	⊕	4.8	5.0		4.6	38		4.3	13		4.8	2.2
Milligan	⊕	4.5	42		4.7	34		4.5	35		4.2	30
Osborn	⊕	4.95	4.8		5.0	2.4		4.9	1.8		7.0	0.0
Boundary	⊕	5.4	1.7		4.7	5.2		4.4	8.8		4.25	11
Prespatou	⊕	6.6	0.1		6.6	0.0		7.1	0.0			
Buick	⊕	4.05	45		4.3	23		4.1	12		3.95	16
Jedney	⊕	4.15	62		4.5	47		4.6	20			

⊕ Typical profiles of soil series from the northern part of the Peace River block in British Columbia provided by T.A. Lord of the Federal Soil Survey in Vancouver. Exact legal locations were not available.